GREEN ROOF WATER HARVESTING AND RECYCLING EFFECTS ON SOIL AND WATER CHEMISTRY AND PLANT PHYSIOLOGY

A Thesis

by

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ABSTRACT

There has been an increase in the utilization of green roofs in the United States due to their abilities to improve the urban environment. Alternative irrigation sources have received a lot of attention over the last decade due to the demanding pressures put on fresh water supplies in urban ecosystems. Alternative irrigation sources can include grey water, sewage effluent (black water) and harvested rainwater which can be a) water captured from an impervious roof and b) stormwater captured from impervious surfaces both of which are stored for later use. This harvested rainwater serves as a freely obtained source of water and can be used for irrigating green roofs. Four intensive green roofs that utilized harvested stormwater and building grey water for use as irrigation in the Houston, TX metropolitan area were examined for their water and soil chemistry and plant physiology. All drainage water or runoff from the roof was captured and returned to the irrigation supply tank so that a recycling system was in place. The green roofs were similar in construction and their water recycling system except that one green roof (roof 1) added the aerobically treated septic discharge onto the roof in addition to the recycling system; while a subset of roof 2 (roof 2B) was unirrigated. A bituminous conventional roof was also included in the investigation to compare runoff quality from green roofs and conventional roofs. Irrigation water, cold-water extracts of growing media, and roof drainage samples were analyzed for their salt and nutrient content. In general, drainage water from the conventional roof had the lowest salt concentrations while roof 1 had the highest salt concentrations in its drainage water. The recycled

irrigation water quality was similar across all green roofs and also similar to municipal tap water from the area. The chemistry of irrigation water samples remained similar throughout the investigation while quality of growing media extracts and drainage water samples from the green roofs showed a strong correlation with the amount of recent precipitation. Containers with identical growing media planted with *Trachelospermum asiaticum* (Asian jasmine) were installed on each green roof to address the concern about different starting media and plant composition on each green roof. Plant water potential, specific leaf area and rates of photosynthesis, transpiration, and conductivity were not significantly different between roofs which helped to further conclude that water quality parameters remained within acceptable boundaries for soil and plant health, regardless of roof age. Container media extract concentrations showed some significant differences for electrical conductivity (EC), percent organic matter, and concentrations of TDN, Mg^{2+}, and Ca^{2+} among roofs yet evidently not enough to influence physiological measurements of plants.

For a study to measure the effect of vegetation and climate on green roof media erosion, green roof modules were installed on a roof in College Station, TX. The presence of vegetation reduced erosion after initial instrument installation yet had little effect once the media settled. Neither windspeed nor precipitation rate had a direct effect on erosion; however, under conditions of high wind and high precipitation an accumulation of media was observed.

DEDICATION

This thesis is dedicated to my parents, family, friends, and my mentors for all their support and encouragement.

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1. INTRODUCTION

Although modern green roofs are a relatively new concept in America, Europe has been incorporating them into urban environments for many years. With the popularity of green roofs in the United States growing, the amount of research being done on green roofs is also increasing (Blank et al. 2013). Since this is still a relatively new field in the industry, much of the research conducted has been aimed at testing what methods work in regards to construction materials and methods, plant species, and media type (Price et al. 2011; Long et al. 2007; Nagase and Dunnett 2011; Dvorak and Volder 2010). Other research has focused on topics such as: storm water retention capacity, runoff water quality, carbon sequestration, urban heat island (UHI) effects, economics related to their insulative capabilities, and their ecological attributes (Rowe 2010; Carter and Keeler 2008; Czemiel Berndtsson 2010; Wong et al. 2003a). The average urban area can have up to 32% roof space (Oberndorfer et al. 2007b). Almost all of this area is impervious, and contributes to the urban stormwater runoff problems not only in quantity but also quality of the runoff.

1.1 Green Roof Components

The FLL Guidelines are formally referred to as the Guidelines for the Planning, Execution and Upkeep of Green Roof Sites (FLLGuidelines 2002). These guidelines were created in Germany but serve as a set of guidelines for green roof construction for many areas. There are two types of green roofs: extensive and intensive. There is no strict dividing line between the two, but according to the FLL Guidelines extensive green roofs typically have a media depth up to 2-20 cm. Extensive green roofs require little maintenance, and are mostly used for their functional attributes rather than their aesthetics. Extensive green roofs typically have carefully selected, stress tolerant plant species requiring little to no irrigation. This type of roof is generally cheaper to construct and often does not require building load reinforcement to support the materials (Wong et al. 2003b; U.S.EPA 2009a). Conversely, intensive green roofs consist of much deeper media 12.5 – 100+ cm, larger vegetation such as small trees and shrubs, and generally require irrigation. Many intensive green roofs are used as roof top gardens accessible to visitors utilizing the space for recreation and gardening (Molineux et al. 2009). Intensive green roofs can be substantially more expensive due to higher construction cost from the added structural reinforcement, more growth media, and more intense maintenance (Bianchini and Hewage 2012).

While there are different types of green roofs, most of them follow a similar profile pattern (Figure 1.1). The bottommost layer - the waterproofing membrane - is to protect the roof from being penetrated by water. On top of this is the drainage layer which allows for enough space for excess water to be drained off the roof. Above the drainage layer lays the filter membrane which functions to keep particles and roots from entering and clogging the drainage layer. Then the engineered media and plants are placed on top of the filter membrane. When working with extensive type roofs, there are different methods to constructing the profiles. For example, a modular system (Figure 1.1 a) uses vegetative trays constructed and cultivated prior to installation and places them on top of a waterproofing barrier which is installed on the roof prior to the modules. The modules contain all the other layers (drainage, filter membrane, media, and plants) within the module. Another method is to treat each profile as a continuous, monolithic layer throughout the entire roof (Figure 1.1 b).

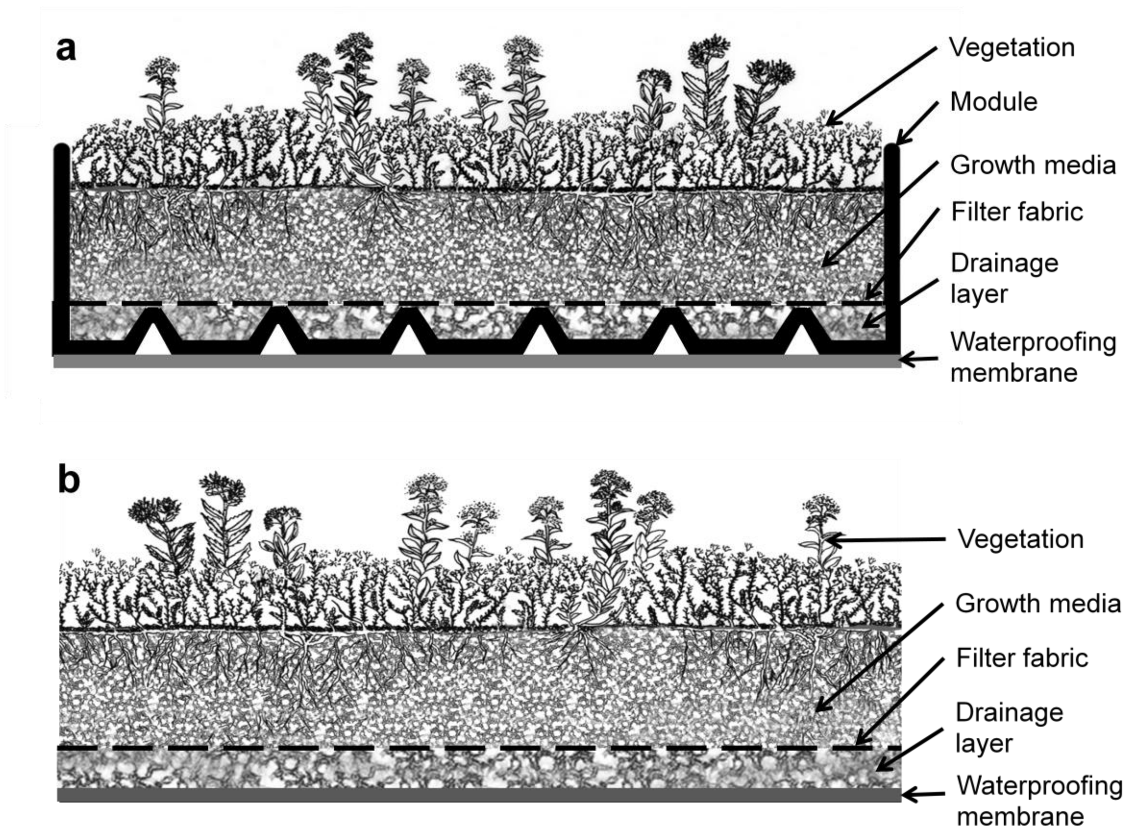

Figure 1.1 Layers of a green roof. The profile of a green roof follows a similar pattern whether it is a modular green roof (a) or a complete/monolithic green roof (b). Modified from Dvorak and Volder (2013)

Green roof media must be lightweight to keep the cost of support structures low. The most common options for use as the mineral soil include fine grade expanded shale or medium grade expanded clay (Long et al. 2007; FLLGuidelines 2002). Organic matter in the media provides nutrients and water holding capacity; however, high organic matter content may also lead to greater nutrient runoff and soil depth reduction (slump) as the organic matter decomposes. Rowe et al. (2006) suggested that no more than 15% of the soil volume in an extensive green roof media should be organic matter. Nagase and Dunnett (2011) noted that 10% organic matter is optimal for extensive roofs. The FLL Guidelines suggested about 4-8% organic matter for extensive roofs and 6-12% organic matter for intensive roofs (FLLGuidelines 2002). The lack of soil formation atop a green roof means that any soil lost must eventually be replaced, leading to increased maintenance costs. A growing medium that holds its structure and does not lose much organic matter through time is desirable. Media loss should be minimized to keep runoff pollution from the roof to a minimum (Aitkenhead-Peterson et al. 2011a; Gregoire and Clausen 2011). Sediments that leave a green roof can contain pollutants and nutrients along with it thereby adding to the nutrient and pollutant load (U.S.EPA 2011).

Plant species selection greatly depends on the climatic conditions of the green roof's location. In many locations, water is the limiting factor determining plant health. Some green roofs rely solely on rainwater as the water supply; therefore selecting plant species with a high tolerance for moisture stress is essential. Succulents have been a popular choice for plantings on green roofs as their leaf structure and ability to use crassulacean acid metabolism (CAM) as the primary mode to assimilate CO_2 leads to reduced transpiration rates and greater water use efficiency. Sedum and delosperma species are some of the most commonly used species on green roofs where low water moisture levels occur (Dvorak and Volder 2010; Oberndorfer et al. 2007a; Snodgrass and Snodgrass 2006). Bousselot et al. (2011) studied moisture level content during a drought period and noted that succulent plants retained more moisture in the growth medium for a longer period of time and had twice as high a revival rate than herbaceous plants. This could be an important characteristic in warm climates in which a green roof might be unirrigated and rainfall is minimal.

Climate and water availability are likely the most limiting factors for many grasses and forbs. Some grasses and forbs are also viable options for use on green roofs (Wolf and Lundholm 2008). Such plants are popular in many landscapes and might be acceptable options on green roofs if such limitations are addressed. Many green roofs are planted with low plant species diversity but such diversity can improve ecosystem functioning (Hooper et al. 2005). Different species might serve different functions in a green roof ecosystem such as pollinator attractor, canopy shading, rootzone biota, erosion control, nitrogen fixation and more. As each species provides such a service then other species can benefit from and compliment another. This is referred to as as multifunctionality and niche complimentary which increases with more species diversity (Lundholm et al. 2010). Multiple species can also increase water retention and absorption benefits (Dunnett et al. 2008; Lundholm et al. 2010). It is not entirely understood why this happens in multispecies plantings but Lundholm et al. (2010) suggest that it is likely though niche complementarity.

The volume of water supplied to a green roof is an important consideration and can vary depending on the climate in which each green roof is located. Green roofs in many northern U.S. climates such as Seattle, Chicago, New York City, and Washington D.C. receive enough intermittent precipitation that an irrigation system may not be necessary. However, green roofs situated in drier and warmer southern climates may need supplemental irrigation to keep the green roof healthy. Some cities such as Houston (1264.16 mm) may receive comparable annual rainfall to northern climates like Seattle (952.3 mm), Chicago (937.0 mm), New York City (1267.5 mm), and Washington D.C. (1008.38 mm). However, much of the precipitation in the Houston, TX area comes from short and intense events while many of the northern climates receive much of their annual rainfall in low intensity yet many intermittent events. Dry periods with little intermittent precipitation can cause plants to decline while intermittent precipitation in the northern climates requires little need for irrigation systems.

A comprehensive healthy plant canopy coverage helps to reduce surface temperatures by limiting direct radiation onto the roof surface thereby adding to the insulative properties of the green roof (Akbari et al. 2001; Susca et al. 2011). In addition, transpiration from a large leaf canopy can reduce surrounding air and roof temperatures (Blanusa et al. 2013; Tabares-Velasco and Srebric 2012; Feng et al. 2010), provided water is available in the roof substrate. Irrigation not only supplies plants with needed water and helps cool the surrounding environment through transpirational cooling, but also directly reduces substrate temperature by evaporative cooling from the substrate (Price et al. 2011). The location of the green roof with respect to climate, desired functions of the green roof, and media depth and composition should be considered when choosing whether or not to install irrigation. Both sprinkler and drip irrigation systems can be used on a green roof. If irrigation is not an option then appropriate materials should be chosen to ensure green roof health and function. For example, this might include plants that can tolerate low soil moisture content and selecting green roof media with a high water holding capacity. Increased soil depth can help reduce rootzone temperatures compared to a more shallow soil. However, soil depth is highly dependent on the structural integrity of the roof (i.e. whether the roof can hold the additional weight).

1.2 Runoff Quantity

Impervious surfaces in urban environments lead to an increase in runoff to surface waters (U.S.EPA 1993). This runoff can overwhelm drainage systems and cause flooding. The runoff water increases peak flow rates in local streams (Arnold and Gibbons 1996) causing stream channels to erode and enlarge (Hammer 1972). There are two types of soil erosion; wind erosion and water erosion. In terrestrial systems, rainfall is the primary cause of soil erosion, and most of this erosion happens when the land is not occupied by plant cover (Zuazo 2008). Runoff transports soil particles that have adsorbed nutrients and comprise organic matter, soil biota, and other mineral particles that can contribute to runoff quality concerns (Sims et al. 1998; Zuazo et al. 2004; Pimentel et al. 1995).

Green roofs can help mitigate storm water runoff. These living roofs act as a pervious surface, replacing the otherwise impervious roof top, retaining and slowing down precipitation and runoff. Over time, plants evapotranspire and soil evaporates water that would otherwise have run off the roof (VanWoert et al. 2005). Green roofs are particularly effective at retaining small rainfall events. During small rain events as much as 70% of the annual precipitation volume was retained by an extensive sedum roof in Pittsburg, Pennsylvania, while during large rain events still as much as 20% of the runoff was reduced, relative to the imperious roof in the study (Bliss et al. 2009). Similarly, Villarreal (2007) showed that as much as 45% and 75% of the annual rainfall could be retained with an extensive and intensive green roof, respectively that was planted with sedums in Lund, Sweden.

Runoff from conventional roofs closely mimics the pattern of rainfall intensity. This delay in runoff start and in the timing of peak runoff reduces the strain put on storm water systems during precipitation events. Another benefit from green roofs is the hydrological delay from when precipitation starts until the time when runoff is observed coming from the roof, as well as a delay when maximum runoff occurs. Carter et al. (2006) showed that average time until peak flow was doubled for an extensive sedum and delosperma green roof compared to a conventional roof located in Athens, Georgia. However, exact timing depends on the size and frequency of rain events, the soil water holding capacity and saturation level of the media, and physiological status of the plants (Schroll et al. 2011).

A systems where all green roof runoff, and perhaps property stormwater runoff, is recycled back onto the green roof would remove loading onto the stormwater system. Such a system would have greater initial expense as it requires a large storage infrastructure, but it will save money long-term as water costs are removed from irrigation costs and those costs are reduced to system maintenance only. In addition, in municipalities that require detention systems, no additional space is required for a detention pond, as the roof and storage system serves as a detention/retention system. In regions where a tax is placed on the amount of water released into the stormwater system, such a system would have large financial benefits (Clark et al. 2008a; Niu et al. 2010). However, the continuous recycling of water through a green roof system in areas with low rainfall, and thus a low refresh rate, could potentially lead to water quality concerns.

1.3 Runoff Quality

Stormwater runoff from roofs, roadways and other structures contains pollutants and contaminates that can be a health threat to humans and the environment (U.S.EPA 1999a). Conventional roofing is a transporter of deposited pollutants such as nitrogen, phosphorus, and metals (Clark et al. 2008b). Metals leached from or washed off impervious roofs and streets account for 50-80% of the mass loadings into drainage systems (Boller 1997). Reducing the volume of water released onto streets from roof tops will reduce the mass of pollutants transported off the streets and into stormwater systems. Other than reducing the volume of runoff, green roofs help reduce the amount of pollutants that are released directly from roofs and enter the stormwater system which eventually enters surface waters. Quality of the runoff from a green roof can vary but it is dependent on the roof's characteristics such as media depth, media composition, drainage, plants species, amount of fertilizer used, roof age, and amount of local environmental pollution (Berndtsson et al. 2006; Morgan et al. 2013). Another environmental benefit of green roofs is their ability to neutralize acid rain in areas where acid rain is a concern (U.S.EPA 2009b). Some studies have found that, when compared to a conventional roof, a green roof can have lower concentrations of nitrate and ammonium (Van Seters et al. 2009; Berndtsson et al. 2006; Gregoire and Clausen 2011) and phosphorus (Gregoire and Clausen 2011) in runoff. Runoff water quality improves with increasing age of the green roof as plants become established and their nutrient uptake is optimum (Kohler 2002). It has been noted that during the first four years after roof establishment that phosphate retention (percent of input) went up from 26.2% in the first year to 79.9% in the fourth year (Kohler 2002).

Green roofs can also export more pollutants compared to conventional roofs. When comparing impervious roof runoff to runoff from green roofs higher concentrations of nitrogen (Aitkenhead-Peterson et al. 2011a; Moran et al. 2004), phosphorus (Van Seters et al. 2009; Hathaway et al. 2008; Berndtsson et al. 2006; Bliss et al. 2009; Moran et al. 2004), organic carbon (Aitkenhead-Peterson et al. 2011a) and sometimes heavy metal concentrations (Alsup et al. 2009; Gnecco et al. 2013) were runoff from the green roofs. Although higher concentrations of pollutants have been observed, the total pollutant load (mg m^{-2}) coming off a green roof can be lower than a conventional roof due to the reduced total runoff coming from the roof (Hathaway et al. 2008). This is referred to as mass loading. The source of the increased concentrations in N, P and organic C generally is organic matter decomposition, and possibly added fertilizer. Organic matter originates from the media and from senescing vegetation, but high concentrations of dissolved organic carbon (DOC) can be leached from the vegetation and minor concentrations are released as root exudates (Aitkenhead-Peterson and Kalbitz 2005). Some nitrogen and phosphorus in the leachate is normal for any vegetated system as organic matter decomposes and releases C, N, and P into soil system. Thus it is not unexpected that nitrogen, phosphorus, and carbon concentrations in runoff of green roofs are higher than in runoff from conventional roofs. The historical land-use or land cover that buildings with green roofs presently occupy probably released similar amounts of nitrogen, phosphorus and organic carbon as the green roofs do. This comparison likely changes when fertilizer is applied to the green roof system. Fertilizer is often applied to green roofs during initial installation and/or replanting. A greater frequency of fertilization and a higher amount of fertilizer applied leads to greater N and P concentrations in runoff coming from green roofs (Hathaway et al. 2008). Thus, if runoff quality is a concern, application of fertilizer should be minimized or skipped completely.

The media and plants that make up the green roof sequester carbon through time. For example, Getter et al. (2009) analyzed the media from a green roof after five years in use and found that organic carbon in the media increased in that period. Sequestered media C is derived from death and decomposition of plants and root exudates. Plants sequester carbon from the atmosphere to use for growth and reproduction. Plants add organic matter to the soil by throughfall, litterfall, root exudation and decay, deposited and plant death. Although plants and soil microbes release carbon in the form of carbon dioxide through respiration, a soil or media can nevertheless increase soil carbon thereby sequestering carbon as an entire system as found by Getter et al. (2009).

Plants influence soil chemistry and hence the quality of runoff, and such influences vary by species. Plants roots exude organic compounds into the soil (Kuzyakov 2002; Aitkenhead-Peterson and Kalbitz 2005) and remove nutrients from the rootzone to support growth and reproduction. When plants were present on a green roof, nitrate concentrations in soil extracts were lower than when plants were absent, suggesting that plants were actively removing nitrate from the media (Aitkenhead-Peterson et al., 2011). Without the presence of plants, the nitrate is left to leach out of the drainage system (Aitkenhead-Peterson et al. 2011a), allowing it to be runoff and contribute to stormflow. Through time, the influence of plants on the retention of nitrogen and phosphorous can increase, presumably because the plants increase in size and thus sequester more nitrogen and phosphorus in their tissues (Kohler 2002). Thus, I would expect older roofs with larger plants and more canopy coverage to have lower nitrate concentrations in runoff. Conversely, as plants gain biomass and plant coverage on the roof is increased, organic matter deposition into the soil may also increase from more biomass senescence and deposition. Even though as a green roof increases its plant coverage it might be taking up more nutrients, it is also depositing more throughfall and litterfall onto the soil thereby adding more nutrients to the soil than when the roof was younger with less plant coverage.

On irrigated green roofs exposed to municipal or stormwater high in salts, there may be an adverse effect on plant health. Sodicity and salinity can have a major effect on plant and soil health. Different soil characteristics and species compositions have different tolerances for salts. Soils affected by salts contain high soluble salts or, most commonly, high concentrations of sodium ions (Na^+). High soluble salt concentrations lower the water potential of the soil to a point where it is difficult for plants to take up water (Stevens and Walker 2002). In soils exposed to sodic irrigation water, sodium ions (Na^+) displace magnesium (Mg^{2+}) and calcium (Ca^{2+}) ions at cation binding sites of soil particles and root membranes (Lambers et al. 2008). As plant tissues accumulate higher concentrations of Na^+, their membranes begin to lose function. For example, Na^+ ions compete with both K^+ ions at transport proteins and also with Ca^{2+} at the cell wall. One role of calcium is to activate the detoxification of Na^+; but when high concentrations of Na^+ are present Ca^{2+} is blocked from doing its job effectively. This results in increasing Na^+ concentrations within the plant and decreasing the ability to effectively alleviate the problem. In terms of saline soils, a concerning element to plant health is chloride (Cl^-). Chloride can have the same effect on the cell as Na^+ but its toxicity effect is generally less extensive (Tester and Davenport 2003). On average, the cytosolic ratio of potassium to sodium and chloride is about 10:1, and in sodic soils the Na^+ and Cl^- can climb to ten times that much (Taiz and Zeiger 2010). Another issue with increasing salts, and one that links nitrogen and salinity, is that Cl^- inhibits the plant uptake of nitrate (NO_3^-)

(Lichtfouse 2009). This would exacerbate the problem of nitrate accumulation within the soil and water system by inhibiting the plant from efficiently taking up nitrogen and could have an effect on plant growth and physiology.

1.4 Green Roofs with Stormwater Harvesting and Recycling Systems

Rainwater collection systems are becoming increasingly popular for use on the landscapes of commercial and residential buildings. Rain that falls onto an impervious surface such as a roof is captured and stored for landscape irrigation later. Harvested rainwater serves as a freely obtained source of water and can be used for multiple purposes including indoor uses such as for drinking, sinks, showers, and flushing toilets, or outdoor uses like irrigating the landscape and other outdoor water uses (U.S.EPA 2008). Depending on the desired use, collected water is treated accordingly to remove contaminants. The most common use of collected rainwater is for landscape irrigation purposes which accounts for 38% of the daily water use of a commercial building (U.S.EPA 2008).

Most green roofs, whether irrigated or not, allow runoff to leave the site. When a water collection system is in use, the roof is usually a hard surfaced conventional roof to allow for as much rain collection as possible. The combined use of water harvesting (stormwater) along with a green roof can be beneficial by supplying irrigation to the plants in times of low rainfall or plant establishment periods. If the collected water is plentiful, then supplemental irrigation can be dispensed to help cool the roof by evaporative cooling and in turn reducing the energy needed to cool the inside of the building (Wong et al. 2003b). However, water quality can become a concern when reusing harvested rainwater that has drained through an organic layer of the green roof. Mendez et al. (2010) compared the runoff from different roofing systems for water harvesting purposes and concluded that runoff from all of the studied roofs (shingle, metal, concrete, green, and cool roofs) would need treatment to meet the U.S.EPA recommended guidelines for non-potable water reuse (U.S.EPA 2004). Irrigation applied to a green roof would likely follow the “restricted” or “unrestricted” category for urban water reuse, depending on whether or not the area is publicly accessible. These guidelines describe the recommended limits of certain pollutants for the irrigation of areas where public access is unrestricted. Currently there are no federal regulations governing water reuse in the U.S. but many states have implemented such regulations. The U.S. Environmental Protection Agency (EPA) does have guidelines for water reuse that summarizes such guidelines with supporting information (U.S.EPA 2004). The Texas Commission on Environmental Quality (TCEQ) does have regulations for quality criteria for specific uses of reclaimed water but not harvested rainwater. The Texas Water Development Board has rainwater harvesting guidelines and recommended quality criteria (TWDB 2006). The important distinction between regulations and guidelines is that regulations are enforceable by law where as guidelines are not.

The combination of a green roof and a water harvesting system is considered a closed system, where water is intercepted by the green roof and drained or runoff to a treatment tank, then into a holding tank where it stays until it is used to re-irrigate the roof. In green roof systems that do not have a method for recycling drainage water, runoff and drainage are not the only avenue for water to leave the green roof system. Water is evaporated from the soil or transpired by plants, where it concentrates the salts and nutrients in the growing medium. Rainwater is low in solutes, but once rain enters the green roof system and begins to infiltrate the soil, the water gains nutrients and salts through leaching and exchanges on soil cation and anion exchange sites. Thus, a concern with continuously recycling harvested rainwater is that the water might become highly concentrated with salts and other pollutants. Electrical conductivity (EC) and sodium absorption ratio (SAR) are two important factors to consider when irrigating with recycled water. Electrical conductivity is a measurement of the ability of a solution to conduct an electrical current. EC increases with increasing amount of soluble salts due to the greater ability of the dissolved salts to conduct electricity. Regularly irrigating with recycled water, generally leads to increasing salt concentrations in the water, which can lead to damage to both plants and soil structure. Stevens et al. (2003) documented a strong increase in both EC and SAR in areas used for agriculture that had been irrigated with reclaimed waste water and concluded that the soil would need appropriate leaching and amendments to ensure a soil quality capable for agriculture purposes. Other studies have investigated the use of harvested stormwater for irrigation and found that this water quality is generally acceptable (He et al. 2008; Khastagir and Jayasuriya 2010).

When harvested then recycled water is not regularly diluted by additional rainfall inputs, such as during periods of drought, water within the recycling system will likely contain an increased concentrations of salts and nutrients (Nicholson et al. 2009). In agricultural or horticultural systems, leaching salts and excess nutrients through the soil profile or flushing a controlled system is the most common method to avoid this build-up. However, in a closed system like a green roof with a water harvesting system and recycling runoff and drainage, leaching or flushing with recycled water to move excess salts and nutrients through the soil profile will not remove salts and nutrients from the system. Rather it will deposit salts and nutrients in the holding tank to be dispersed onto the soil during future irrigation cycles as there is no avenue for salts to leave the system. Precipitation input will dilute the salts but not remove them.

1.5 Green Roof Media Erosion

The loss of roof media in dry environments through water and wind erosion has received little attention. In natural systems, precipitation is a primary cause of soil erosion, and most of this erosion occurs when the soil surface is bare (Zuazo 2008). Wind is another contributor to soil erosion, particularly if the soil is bare. Wind speed and turbulence, ground cover, surface roughness and soil structure, texture and moisture content are all important factors determining the extent of soil erosion due to wind (Chepil 1945). Erosion by wind is especially pronounced in areas with little vegetation and coarse soils (Breshears et al. 2003).

Many extensive green roofs in warm parts of the U.S. tend to resemble an environment typical of arid landscapes, especially during summer months when conditions are hot and dry. The shallow media depth, coarse media type, and lack of irrigation require installed vegetation to be tolerant of high temperatures and low soil moisture. Wind speed atop a roof is usually greater than at ground level due to higher elevation and exposure (Sutton 2008; Dunnett and Kingsbury 2004). Soils with little organic matter, which is typical of coarse soils, are most susceptible to wind erosion (Liu et al. 2006). Green roof media, especially media used on extensive types of green roofs, are typically a coarse, grainy mineral based media with little organic matter to allow the media to stay within weight restrictions while still being able to retain moisture to support plant life (Farrell et al. 2012; FLLGuidelines 2002). Precipitation and irrigation help reduce wind erosion by weighing down the soil and bonding soil particles to each other (Zobeck 1991). However, when precipitation exceeds the infiltration rate then surface runoff may occur leading to soil erosion.

A pattern of less frequent but more intense rain events, as projected by global climate change (IPCC 2007; Groisman and Knight 2008), could increase water and wind erosion because, 1) larger, more intense, rain events could exceed the infiltration rate and cause increased soil erosion by water, and 2) more intense and prolonged drying periods could lead to increased incidence of conditions that promote soil erosion by wind. The lack of soil formation and/or sediment deposition atop a green roof means that any media lost must eventually be replaced, adding to the cost of green roof maintenance.

1.6 Study Locations and Objectives

1.6.1 Site 1: Houston

Four green roofs in the southeast area of Houston, Texas were investigated for their utilization of a rainwater harvesting and recycling system. Each roof uses the same type of water harvesting and recycling system for use as irrigation (Figure 1.2). Rainwater was collected from the surrounding parking lot (stormwater runoff) and roof along with grey water from the building and is stored in holding tanks. Prior to being used as irrigation the water passes through a sand filter. Once dispersed on the roof as surface irrigation, water percolates through the plant and media layers where it then drains back into the holding tank. Few studies have been conducted on green roofs that are irrigated with a combination of harvested rainwater and grey water. The objectives of this study were:

1. Quantify whether the green roof growth medium, storage water, and drainage water shows a buildup of salts and nutrients. Runoff samples, media samples, and irrigation samples were taken to better understand the nutrient cycling of the green roof systems.
2. Determine whether the recycled irrigation had an effect on plant physiology. Water potential and photosynthesis measurements were taken from the same species on each roof. Older roofs were expected to have lower quality irrigation since they have been recycling water for a longer period of time thereby concentrating salts and nutrients in the water. The physiology measurements were to test whether the irrigation was having different effects on plants between roofs.

1.6.2 Site 2: College Station

This project takes place at the Texas A&M University Langford Architecture building in College Station, Texas. Media erosion was measured in green roof modules that were located on top of the building. There were 4 planting treatments to test whether functional group or species composition had an effect on erosion. My objective at this site was:

1. Examine whether the use of plants on a green roof can help prevent or reduce soil erosion and if functional group composition (succulents, herbaceous, or mixed) has an effect on erosion processes.

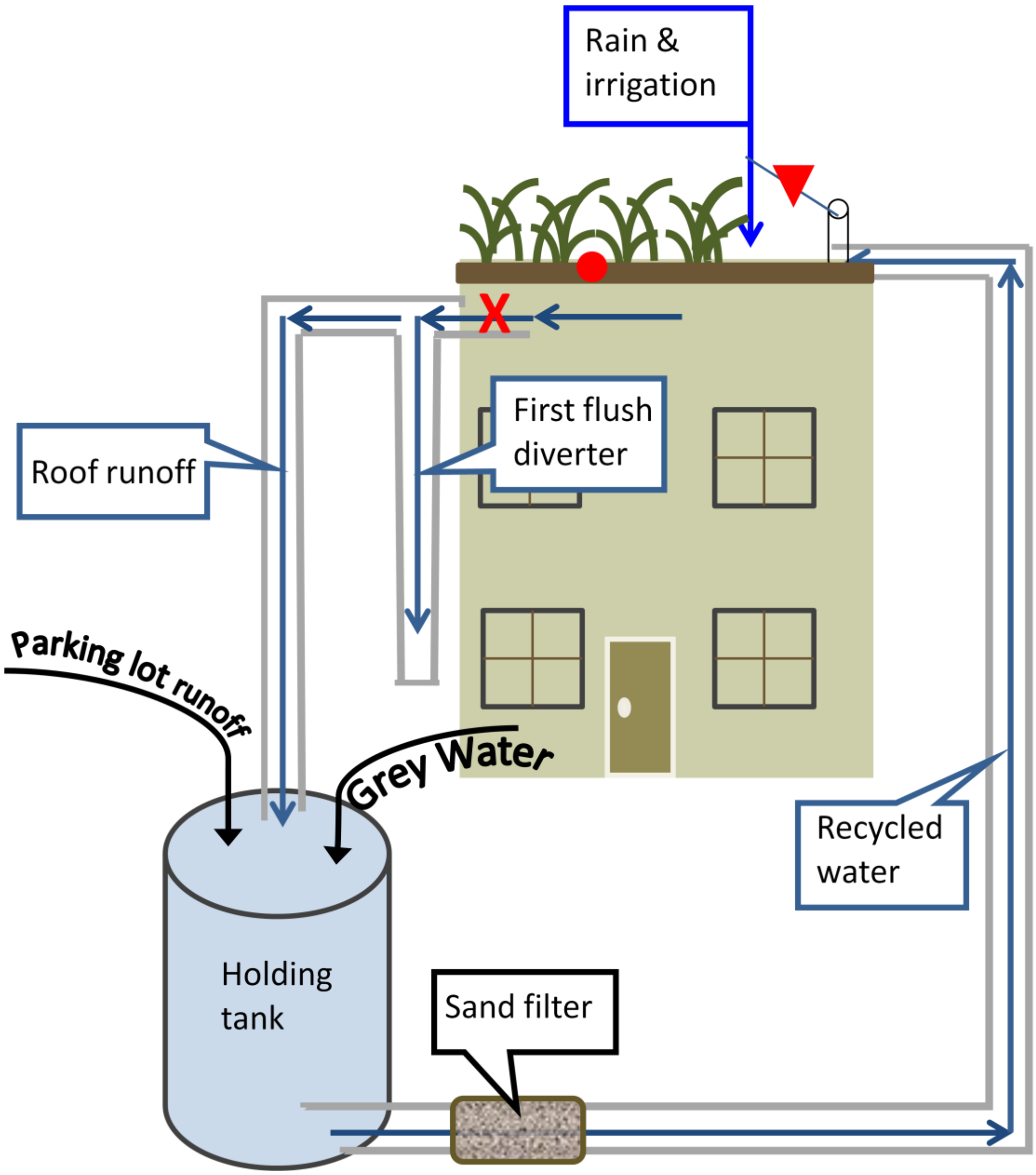

Figure 1.2 Green roof water harvesting and recycling system. All roofs utilize this recycling system while Roof 1 also adds the aerobic septic system spray onto the roof. Water is captured by the roof and parking lot and stored in the holding tanks. It is then passed through a sand filter before being dispersed as irrigation. Points of sampling were irrigation (triangle), media core (circle), and roof runoff (X).

1.7 Summary

The overall goal of my research was to determine the effectiveness of water harvesting and recycling systems for use on green roofs. More specifically, section 2 addresses questions related to the soil and water quality when using recycled water for irrigating green roofs. I will evaluate whether continually recycling harvested rainwater from a green roof negatively influences water chemistry and/or leads to a decline in media health. In Section 3, I will assess whether the green roofs' recycling systems have an effect on plant function and physiology, while in section 4, I will examine erosion processes on extensive, modular green roof systems. Finally in section 5 I place all my findings in the context of soil, water and vegetation management on green roofs, as well as the potential for continuous recycling systems to be incorporated into green roof infrastructure as another means of environmental benefits provided by green roofs.

2. EFFECTS OF A WATER HARVESTING AND RECYCLING SYSTEM ON GREEN ROOF WATER AND SOIL CHEMISTRY

Environmental awareness has brought about best management practices (BMPs) that aim to reduce our ecological impact. The southern United States has experienced several extreme droughts in recent years (NOAA 2013). Such droughts can expose all landscapes to water shortages. This is especially true for designed urban landscapes on which cities place temporary ordinances to limit water use. Systems that catch rainwater from impervious surfaces and store it for future use take advantage of a water source that is otherwise discarded. Rainwater harvesting can be utilized on any scale whether it is a residential sized roof or a commercial building. Collected rainwater can be used for many things, but the most common use is for irrigation purposes which can account for 38% of the daily water use of a commercial building (U.S.EPA 2008).

Most green roofs, whether irrigated or not, allow runoff or leachate to leave the site (Hardin et al. 2012). The combined use of rainwater harvesting along with a green roof can be beneficial by supplying irrigation to the plants in times of low rainfall or during plant establishment periods. In addition, it reduces or even eliminates the release of runoff into the stormwater system, thus reducing downstream problems associated with large amounts of runoff (Hammer 1972; Arnold and Gibbons 1996). Supplemental irrigation with harvested rainwater can also be used to help cool the roof through evaporative cooling from wet soils. This, in turn, will reduce the energy needed to cool the inside of the building (Wong et al. 2003b).

One major concern with continuously recycling water is that the water might become highly concentrated with salts, nutrients and other pollutants due to its repeated percolation through the organic growing medium (Mendez et al. 2010). In a system where runoff is recycled back onto the roof, the only avenues for water to leave the system are evaporation out of the soil, or transpiration out of the leaves, while the only external input that could dilute the water comes from precipitation. Evapotranspired water leaves behind most solutes, therefore concentrating these solutes in the system unless additional precipitation dilutes the solutes. While initial precipitation are low in solutes, once precipitation enters and interacts with the vegetation and soil system, quality of system water should be expected to decrease. Water within the system might also be expected to contain higher concentrations of salts and nutrients during periods of lower water input into the system (Nicholson et al. 2009). During a drought, little precipitation occurs to dilute the system, yet water is recycled through the roof media as irrigation. In agricultural or horticultural systems, leaching salts and excess nutrients through the soil profile or flushing a controlled system is the most common method to avoid a build-up of salts. However, in a semi-closed system like the green roofs, leaching or flushing the system to move these nutrients through the profile will not cause them to leave the system. They will accumulate in the holding tank and be dispersed onto the soil during future irrigation cycles.

A semi-closed system completely eliminates the release of runoff pollutants into municipal stormwater systems and local streams which has been an issue with some green roofs (Moran et al. 2004; Van Seters et al. 2009; Berndtsson et al. 2006; U.S.EPA

2009b) . However, potential growing media salinity problems could have negative effects on water and media quality, and, by extension, plant growth. Thus, the first objective of this study was to determine if runoff from a conventional roof compare to a non-irrigated green roof's runoff, and a green roof irrigated with recycled water. We hypothesized that the conventional roof will have lower salt and nutrient concentrations in its runoff than the green roofs. The second objective was to evaluate the effects a water harvesting and recycling system will have on water quality and soil chemistry on a green roof. We hypothesized that 1) the non-irrigated green roof will have less salt and nutrient accumulation than the green roof that is receiving recycled water, 2) recycling harvested rainwater will cause the salt and nutrient concentrations to increase in the growth medium and irrigation, and, 3) the older roofs will contain a higher concentration of salts and nutrients than the younger roof

2.1 Materials and Methods

2.1.1 Site Characteristics

Four green roofs and one conventional roof made of bituminous asphalt are located in the southeast Houston, TX area were investigated (Figure 2.1). The experiment was conducted from July 2011 through November 2012. Each green roof is similar in composition and construction. All four green roofs were constructed with the same soil mix and very similar plant composition (Table 2.1). Each green roof has a slope of 2%. The growing media (Nature's Way Resources, Green Roof Mix, Conroe, TX), had an organic matter content of 5-8%, with 40-50% fine, mineral soil and 50-60% gravel.

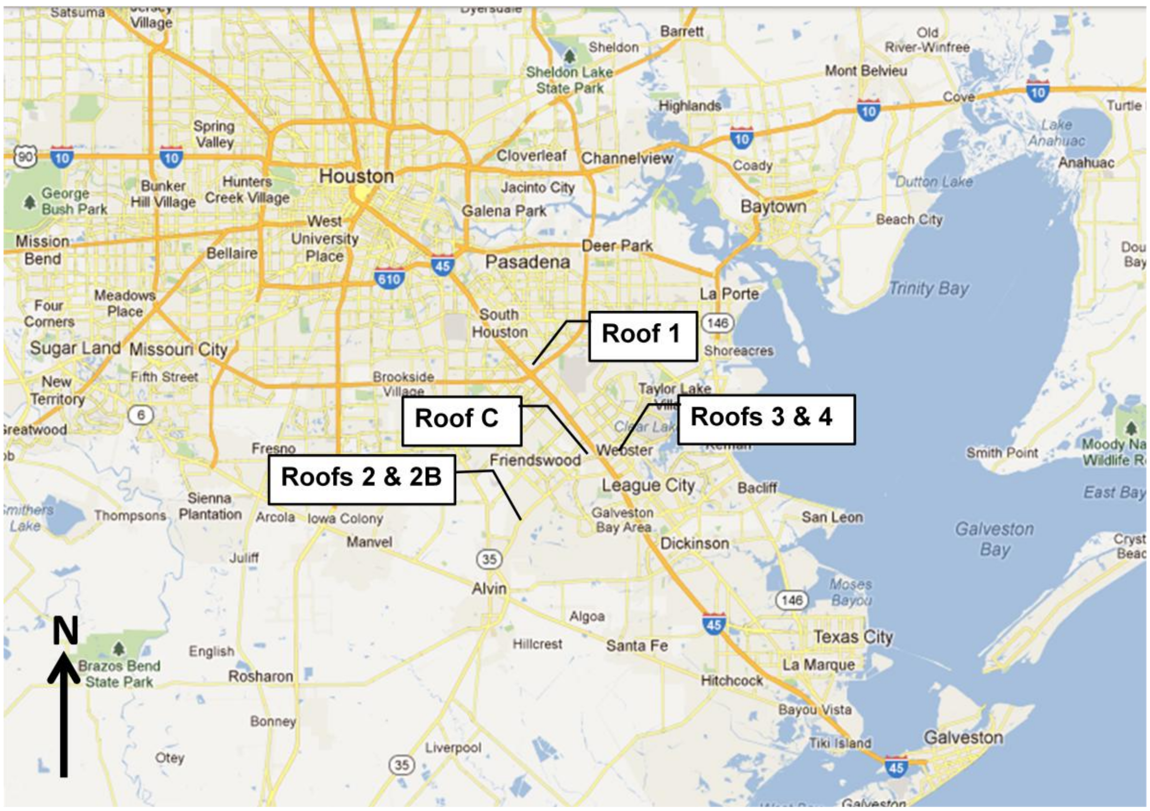

Figure 2.1 Map showing locations of the roofs used in the study. Google Maps® accessed on February 5, 2014

2.1.2 Water Harvesting and Recycling Systems

Each building (with the exception of the conventional building) was equipped with a rainwater harvesting and recycling system that harvests precipitation runoff from the roof and adjacent parking lots and used this water to irrigate the green roof and surrounding landscape of the building (Figure 1.2). Grey water (sinks, air conditioning condensate) from each building was also stored in the holding tank. The holding tanks consist of a thick plastic bladder stored inside a concrete shell which is stored underground. The size of the holding tanks varies per building. Before being stored in holding tanks all water (grey water and harvested runoff) passes through a screen to remove debris and large particles. A first flush diverter is located near the roof downspout leading to the holding tanks. The diverter collects the first flush of water and debris that comes from the roof during a runoff event, once the diverter is full, water then enters the holding tank. The first flush water is released onto the parking lot and enters the belowground holding tanks with parking lot runoff, while large debris is collected regularly and thrown away. This system prevents roof debris from clogging up pipes and screens. The water is then stored in holding tanks until it is used for irrigation. Before being dispersed as irrigation, water passes through a sand filter. The roofs and landscape surrounding the building are irrigated using overhead spray irrigation. Water that falls onto each roof percolates through the plant and soil layers where it then drains back into the tank and is recycled. Most of the four study green roofs' systems function similarly with the exception of some characteristics (Table 2.1). Roof 1 is the site of a septic system sprinkler in addition to the water harvesting and recycling system. Septic waste is treated aerobically in a separate compartmentalized unit and then uses the effluent water as an additional source of irrigation. Roof 2B is a separate elevated portion of Roof 2 that receives no irrigation.

Table 2.1 Construction date, roof age at the end of the experiment, species composition, irrigation water source and mean media depth for each roof in the study

Roof	Date constructed	Age at time of experiment's completion	Species composition†	Irrigation	Mean Media Depth (cm)
Roof 1	Dec. 2010	1 year, 11months	*Muhlenbergia capillaris* *Tradescantia pallida* *Ruellia brittoniana*	recycled & aerobic septic treatment spray	12.95
Roof 2	Dec. 2008	3 years, 11 months	*Muhlenbergia capillaris* *Trachelospermum asiaticum* *Buxus microphylla* *Lantana spp.* *Plumbago auriculata*	recycled	16.97
Roof 2B‡	Dec. 2008	3 years, 11 months	*Muhlenbergia capillaris*	none	14.69
Roof 3	Aug. 2007	5 years, 3 months	*Muhlenbergia capillaris* *Liriope muscari* *Lantana spp.*	recycled	18.98
Roof 4	Mar. 2005	7 years, 8 months	*Muhlenbergia capillaris* *Liriope muscari* *Lantana spp.*	recycled	12.14
Roof C	June 1983	29 years, 5 months	-	-	-

†Species are in order of decreasing abundance
‡Roof 2B is a separate elevated portion on the same building as Roof 2

2.1.3 Water Collection

Irrigation samples and green roof drainage water runoff samples were collected a total of eight times over the one year period. Irrigation samples were obtained by turning on the irrigation system and collecting the water straight from the sprinkler head. Runoff samples were collected by placing collection cups in the drains of each roof. Three collection cups were placed on each roof in different drains with the exception of Roof 2B where we installed only two collection cups due to the number of drains. The collection cups were placed about 30-60 cm deep in the drain to avoid exposure to sunlight. Drainage water in the collection cups was transferred to HDPE bottles and stored in iced coolers. Once at the lab, electrical conductivity (EC) and pH were determined. Water samples were then filtered through a Whatman 0.7 micron filter into clean HDPE bottles and frozen for later analysis. Samples were analyzed for dissolved organic carbon (DOC), total dissolved nitrogen (TDN), ammonium-N (NH_4-N), nitrate-N (NO_3-N), dissolved organic nitrogen (DON), phosphate-P (PO_4-P), alkalinity, and sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}) ions. Dissolved organic nitrogen (DON) and sodium adsorption ratio (SAR) were calculated. DON was calculated by subtracting the sum of ammonium-N and nitrate-N from the total dissolved nitrogen (DON=TDN-[ammonium-N + nitrate-N]). Sodium adsorption ratio (SAR) estimates the sodium ratios in the soil solution and is also used to estimate the quality of irrigation waters. The equation for determining sodium adsorption ratio is $SAR=Na^+ / [(Ca^{2+} + Mg^{2+})/2]^{1/2}$ where Na^+, Ca^{2+}, and Mg^{2+} are soluble ionic concentrations in mmol L^{-1} (Bower 1959). A Shimadzu TOC-VCSH Total Organic Carbon Analyzer with a TNM-1 Total Nitrogen Detector was used to determine total organic carbon and total dissolved nitrogen. Phosphate-P, nitrate-N, ammonium-N, and alkalinity were analyzed using a Westco Smartchem Discrete Analyzer. A Dionex IC 1000 was used to quantify cations: Na^+, K^+, Mg^{2+}, and Ca^{2+}.

I was unable to differentiate between drainage samples that occurred either due to irrigation or rainfall events. I visited the roof every one to two months to collect samples and some precipitation occurred at least every month while irrigation was run every week at the minimum, but often two times per day during the warm season. Thus the drainage samples contain a mixed sample of runoff due to precipitation and runoff due to recycled water (Figure 2.2).

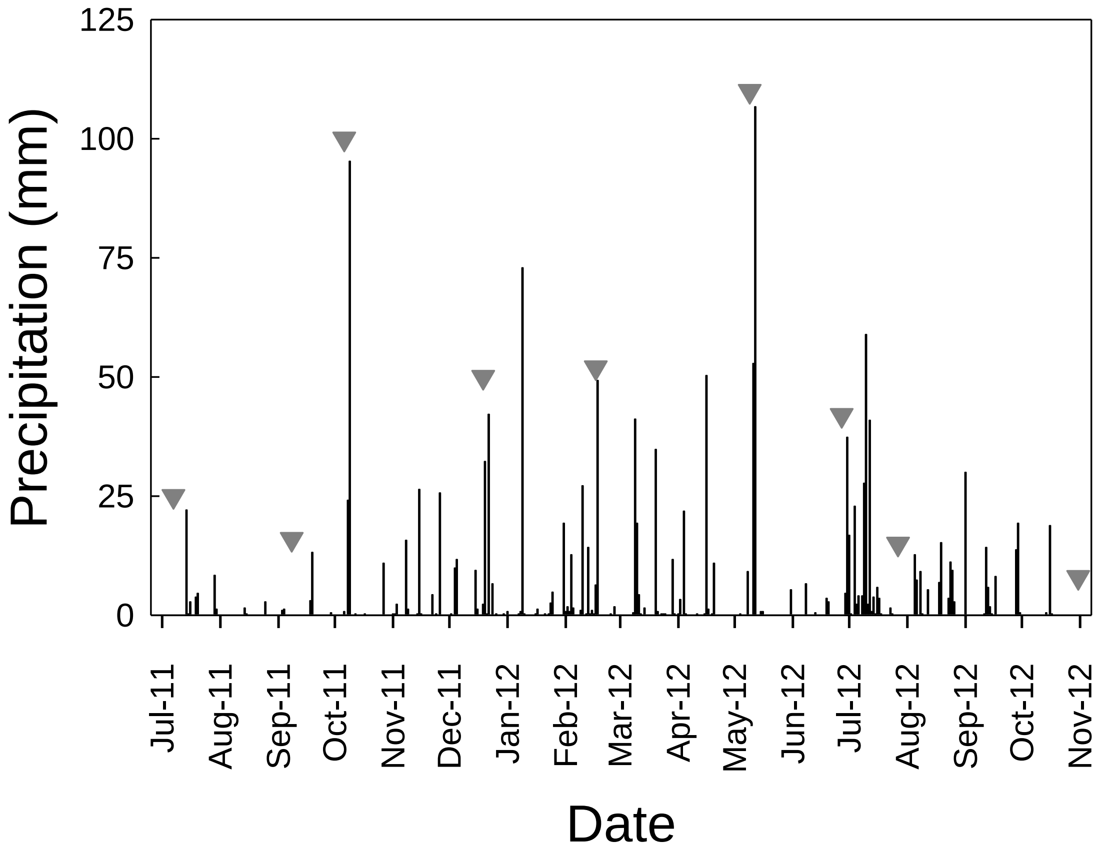

Figure 2.2 Precipitation per day (mm) during the measurement period (July 2011-November 2012). Triangles indicate sampling dates

2.1.4 Soil Samples

Soil samples were collected using a manual core (25.4 mm diameter) on every roof throughout the experimental period on the same dates water samples were obtained.

Cores were taken to depth of refusal and soil depth measured. Soil samples were placed in an iced cooler and transported to the lab the same day. Soil sub-samples were weighed and then oven dried at 50 ºC. Percent moisture was determined by weighing samples before and after at least 24 hours in the drying oven. The difference between the weight before and after the oven was considered water weight. Air dried samples were passed through a 2 mm sieve to separate the fine soil from the gravel. Percent fine soil and percent gravel were calculated for each sample. Percent organic matter was determined through loss-on-ignition by placing samples in a furnace and heating to 450 °C for four hours (Ball 1964).

2.1.5 Soil Extractions and Processing

Soil extractions were performed using a soil:water ratio of 1:10. Three grams sieved, air-dry soil was combined with 30 g ultrapure water (Barnstead Model, Thermo Scientific, Waltham, Massachusetts) in 50 mL centrifuge tubes. The soil:water mixture was then shaken for 1 hr at 50 rpm. Samples were then centrifuged at 10,000 RPM for 15 minutes at 4°C. The supernatant (extract) was pulled from the centrifuge tube using a canula and syringe and electrical conductivity (EC) and pH of the extract were determined. The extracts were then passed through a Whatman GFF 0.7 micron filter into clean HDPE bottles. Water was added to the extract as a dilutant to yield enough sample needed for analysis. Samples were frozen until analysis. Soil extracts were analyzed in the same manner as drainage and irrigation water samples.

2.1.6 Data Analysis and Statistics

All statistical analyses were performed using JMP statistical software (JMP 7.0, SAS, Cary, NC). Effects of roof location on irrigation, runoff, and growth media salt content were analyzed through one way ANOVA, after which differences between means were determined using a student's t-test. Effects of roof location and precipitation input on irrigation, runoff, and growth media salt content were analyzed through two-way ANOVA, where the preceding intervals mean daily precipitation was used as a continuous variable. A *P*-value less than 0.05 was assumed to indicate significance significant effect of roof or precipitation input. Results were plotted using SigmaPlot 9 (Systat Software Inc., San Jose, CA).

2.2 Results

2.2.1 Media Chemistry

The conventional roof, roof C, is not included in the media and irrigation water analysis since it had neither media nor irrigation. Roof medium extract analysis showed that none of the parameters measured were significantly different among green roofs, except for percent organic matter (Table A-1). The two youngest roofs, roof 1 and roof 2, had a higher mean percent organic matter (7.4 and 7.1%, respectively) compared to the other three roofs ($P < 0.001$) (Figure 2.3b). Initial growing media used on all the green roofs was obtained from the manufacturer and analyzed against samples taken from the roofs (labeled *Initial mix* in Figure 2.3 a-c). Electrical conductivity of the initial mix was significantly higher than all green roofs with a mean EC of 315 µS cm^{-1} while the green roofs' EC ranged from 129.8 – 167.4 µS cm^{-1} (P = 0.018, Figure 2.3a). Organic matter content of the initial growing mix was significantly lower (P < 0.001) than roofs 1 and 2 but not roofs 2B-4 (Figure 2.3b). Mean Ca^{2+} concentration in initial growing media was significantly higher than all green roofs (P = 0.002). Mean Ca^{2+} concentration of the initial mix was 344.6 µg g^{-1}, while the other green roofs ranged from 123.4 – 161.6 µg g^{-1} (Figure 2.3c).

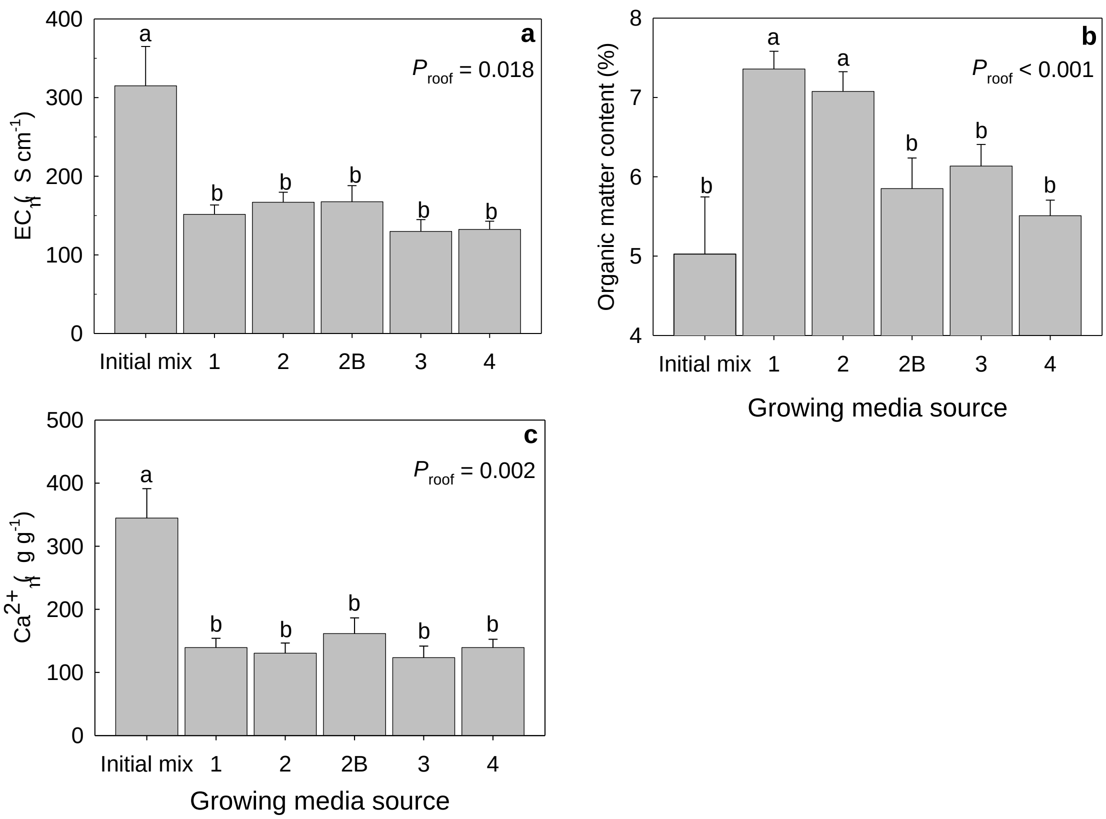

Figure 2.3 a) EC of media extracts, b) organic matter content of media and c) calcium ion concentration of media extracts. Roofs are in order of roof age. Differences between roofs are indicated by different letters as determined by Student's t-test at P < 0.05. Thin bars indicate standard error

Precipitation effect on growing medium

The average daily precipitation (mm day^{-1}) had significant effects on most of the parameters and constituents measured (Figure 2.4, Table 2.2), except pH, percent organic matter, TDN, NO_3-N, and alkalinity. In general, EC of the extract and salts in the extracts decreased as mean daily precipitation in the time interval increased (Figure 2.4, Table 2.2), with the exception of DON. As mean daily precipitation increased, the concentration of DON (μg g^{-1}) in the growing media also increased (P = 0.006, Figure 2.4e). The response to precipitation was the same across roofs except for DOC where there was a roof by precipitation interaction (P = 0.036). This effect was due to one measurement on Roof 4 that accounted for the significantly different effect precipitation per day had on this roof compared to Roofs 1, 2, 2B and 3 (circled in Figure 2.4c). When this measurement is excluded from the model, the roof by precipitation interaction is removed (Table 2.2).

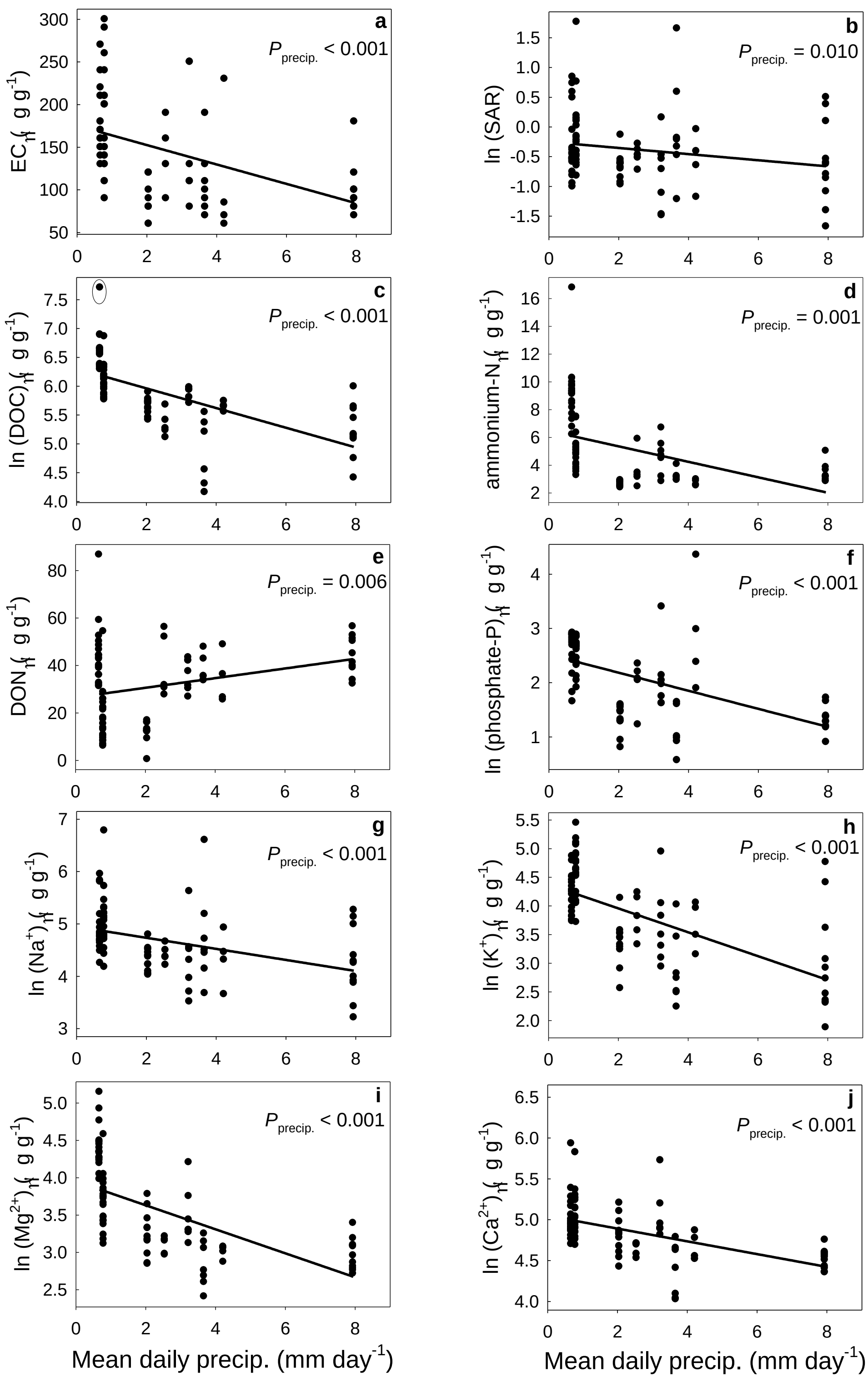

Figure 2.4 Effect of mean daily precipitation on green roof media extract chemistry. The circle in figure c) indicates an outlier that was removed prior to statistical analysis (Table 2)

Table 2.2 *P*-values of roof and precipitation per day on each analyzed parameter of green roof growing media. Significant differences between parameters are indicated in bold type at $P < 0.05$ as determined with a Student's t-test from two-way ANOVA, where preceding intervals mean daily precipitation was used as a continuous variable

	pH	EC (μS cm^{-1})	ln(DOC) (μg g^{-1})	ln(DOC) excl. outliers (μg g^{-1})	TDN (μg g^{-1})	NH_4-N (μg g^{-1})	NO_3-N (μg g^{-1})	DON (μg g^{-1})	ln(PO_4-P) (μg g^{-1})	Alkalinity (μg g^{-1})	ln(Na^+) (μg g^{-1})	ln(K^+) (μg g^{-1})	ln(Mg^{2+}) (μg g^{-1})	ln(Ca^{2+}) (μg g^{-1})	%OM	ln(SAR)
Roof	0.741	0.160	0.737	0.502	0.424	0.332	0.055	0.451	0.089	0.410	0.662	0.920	0.666	0.481	**<0.001**	0.754
Precip	0.685	**<0.001**	**<0.001**	**<0.001**	0.734	**<0.001**	0.162	**0.006**	**<0.001**	0.792	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.357	**0.010**
Roof*Precip	0.969	0.209	**0.036**	0.066	0.956	0.711	0.204	0.392	0.690	0.228	0.621	0.305	0.836	0.798	0.467	0.637
Model P	0.978	**0.002**	**<0.001**	**<0.001**	0.816	**0.002**	**0.047**	0.083	**<0.001**	0.341	**0.015**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.391
Model R^2	0.033	0.295	0.513	0.519	0.067	0.299	0.203	0.184	0.384	0.126	0.240	0.504	0.414	0.343	0.421	0.120

Effect of plant species on growth medium chemistry

Species effect was examined within each roof as species composition varied between roofs (Table A-2). The only parameter affected by species composition was organic matter percentage, but only on Roof 3 ($P = 0.020$). Media samples taken from under and around *Lantana spp.* and *Liriope muscari* had a higher mean percent organic matter (7.4% and 6.7% respectively) than samples from *Muhlenbergia capillaris* (5.5%).

2.2.2 Runoff Quality

In general runoff from the conventional roof was lower in salt and nutrient concentrations than the green roofs (Figure 2.5). All green roofs had significantly higher electrical conductivity in runoff compared to the conventional roof ($P < 0.001$). Mean runoff EC from the conventional roof was 62.6 µS cm^{-1} while the green roofs' mean EC ranged from 421-832 µS cm^{-1}. Roof 1, the roof that used septic spray as an irrigation source, had a significantly higher mean EC than any of the green roofs (832.1 µS cm^{-1}). The EC of the remaining roofs (Roof 2, Roof 2b, Roof 3, and Roof 4) were not significantly different from each other. The mean pH of the conventional roof's runoff was not significantly different from that of the green roofs' runoff with the exception of Roof 4 – the un-irrigated green roof ($P = 0.009$). Every green roof, except Roof 4, had a higher mean concentration of DOC in the runoff compared to the conventional roof ($P < 0.001$). Total dissolved nitrogen (mg TDN L^{-1}) and nitrate-N (mg NO_3-N^- L^{-1}) was not statistically different among roofs with the exception of Roof 1 which had a higher concentration of both constituents in drainage water than all roofs ($P < 0.001$). The mean concentration of ammonium-N in the drainage water was not different among roofs. The mean concentration of dissolved organic nitrogen was significantly lower in the conventional roof's runoff than any of the green roofs ($P < 0.001$) with the exception of Roof 1 from which it was not significantly different. Phosphate-P concentration (mg PO4-P L^{-1}) in the drainage from the conventional roof was only significantly lower than Roof 1 and Roof 2 ($P < 0.001$). Potassium ion (K^+) concentration in the runoff from the conventional roof was only significantly lower than Roof 1 and Roof 2b (the septic spray roof and the unirrigated roof) ($P < 0.002$). All green roofs had an order of magnitude higher mean alkalinity in the runoff compared to the conventional roof ($P < 0.001$). With the exception of Roof 2b, all green roofs had a higher mean concentration of sodium in the runoff than the conventional roof ($P < 0.011$). The conventional roof had significantly lower concentrations of both calcium and magnesium in the runoff than all the green roofs ($P < 0.001$, both constituents). The sodium absorption ratio was not significantly different among roofs.

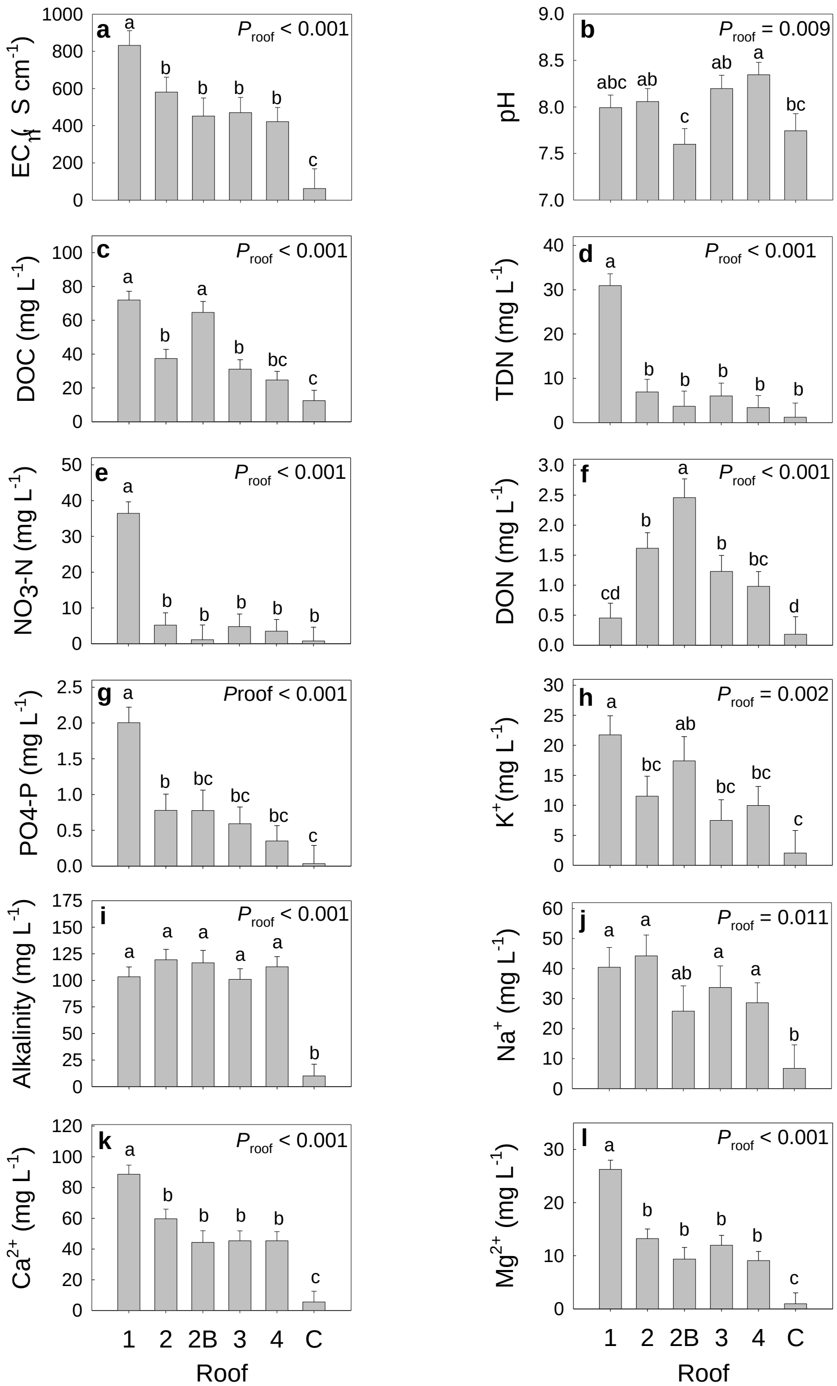

Figure 2.5 Nutrient concentrations in roof drainage water averaged over nine collection dates from July 2011 – November 2012. Roofs are in order of increasing age, 1-4 are vegetated roofs, roof C is conventional roof. Only parameters that differed significantly between roofs are shown. Differences between roofs are indicated by different letter as determined by Student's t-test at $P < 0.05$. Thin bars indicate standard error

2.2.3 Irrigation

Roof 2B is not included in the irrigation water analysis since it received no irrigation. The pH, DOC, TDN, DON, alkalinity, and SAR of irrigation water were not significantly different among green roofs. Roof significantly affected EC, NO_3^--N, NH_4^+-N, PO4-P, Na^+, K^+, Ca^{2+}, and Mg^{2+} (Figure 2.6**)**. The oldest roof, Roof 4, had a significantly lower irrigation water EC (P = 0.007) with a mean of 249.5 µS cm^{-1} while the other green roofs' EC was 438.9 µS cm^{-1}, 527.4 µS cm^{-1}, and 433.3 µS cm^{-1}, respectively in order of increasing roof age. Nitrate-N and phosphate-P concentrations were significantly higher in irrigation water used on roofs 2 and 4 (P = 0.015 and P = 0.001, respectively) (Figure 2.6b and 2.6d). Ammonium-N concentrations showed the opposite trend and were higher in roof 1 and roof 3 (P < 0.001). Sodium concentrations were marginally significantly different between roofs (Figure 2.6e). Roof 4 had lower Na^+ concentrations in irrigation water than roofs 2 and 3 but not significantly different than roof 1. Roof 4 had highest K^+ concentrations in irrigation while the other 3 roofs were not significantly different from each other (P = 0.054, Figure 2.6f). Roof 2 had a higher Ca^{2+} and Mg^{2+} concentration than the other three roofs (P < 0.001 and P = 0.011, respectively) (Figure 2.6g-h). Roof 4 had the lowest Ca^{2+} concentration while roofs 1 and 3 were not significantly different from one another. Other than roof 2 having the highest Mg^{2+} concentration of irrigation water, the Mg^{2+} concentrations of irrigation water on roofs 1, 3, and 4 were not significantly different from each other. Recycled irrigation from the roofs was very similar to municipal tap water obtained from building 2 (Figure 2.6, Table A-3).

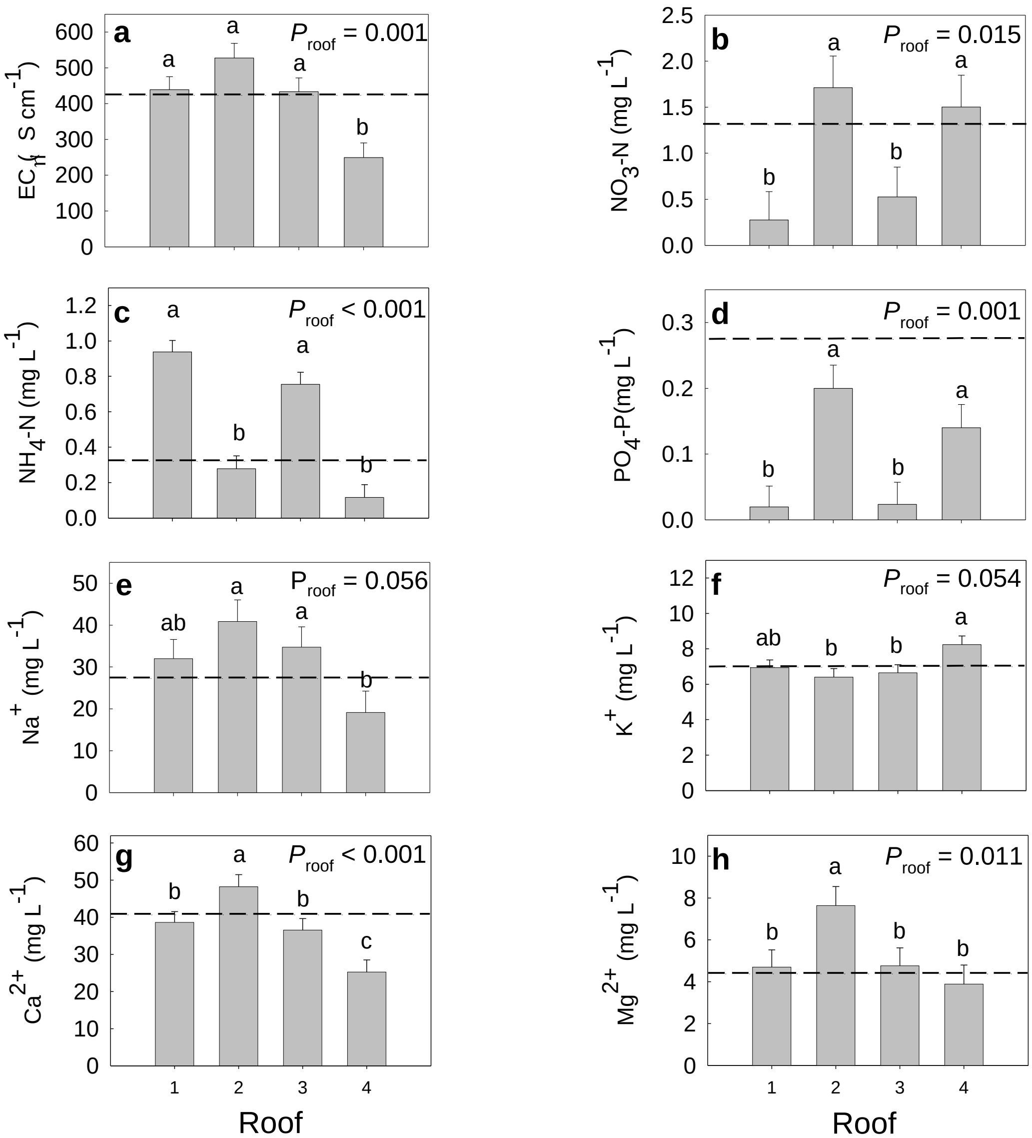

Figure 2.6 a) irrigation water EC, and mean concentrations of b) nitrate-N, c) ammonium-N, d) phosphate-P and e) Na^+ f) K^+ g) Ca^{2+} h) Mg^{2+} by roof over the full experimental period (n=8, July 7, 2011 – November 1, 2012. Roofs are in order of increasing age. Dotted horizontal line indicates the mean concentration measured in municipal tap water from the building of roof 2. Only significantly different parameters are shown and are indicated by different letter determined by Student's t-test at $P < 0.05$. Error bars indicate standard error

Effect precipitation on irrigation chemistry

There was no effect of mean daily precipitation or roof on pH of the irrigation water. Potassium was the only ion in irrigation water that was similarly affected by precipitation ($P = 0.017$) across roofs ($P_{\text{interaction}} = 0.510$). DOC, TDN, and DON all showed a roof by precipitation interaction (Table 2.3, Figure 2.7a-c) ($P = 0.003$, $P < 0.001$, $P < 0.001$ respectively). However, one outlying sample collected on roof 4 appeared to drive this interaction (circled in Figure 2.7a-c), causing roof 4 to have unusually high DOC, TDN and DON concentrations after periods of high mean daily precipitation. When this sample was removed from the statistical model, the roof by precipitation interaction and the overall effect of precipitation were removed (Table 2.3). Both Mg^{2+} and Ca^{2+} also showed a roof by precipitation effect in irrigation water ($P = 0.002$, $P = 0.023$ respectively). However, when the same two samples (circled in Figure 2.7 e-f) were excluded from the model the roof by precipitation interaction was removed from both Ca^{2+} and Mg^{2+}.

Table 2.3 *P*-values of the effect of roof and precipitation/day and their interaction on each analyzed parameter of green roof irrigation. Bold type indicates significant difference between treatments within a factor at $P < 0.05$ as determined by Student's t-test

	pH	EC ($\mu S\ cm^{-1}$)	DOC ($mg\ L^{-1}$)	DOC excl. outlier ($mg\ L^{-1}$)	TDN ($mg\ L^{-1}$)	TDN excl. outlier ($mg\ L^{-1}$)	NH_4-N ($mg\ L^{-1}$)	ln(NO_3-N) ($mg\ L^{-1}$)	DON ($mg\ L^{-1}$)	DON excl. outlier ($mg\ L^{-1}$)	PO4-P ($mg\ L^{-1}$)	Alkalinity ($mg\ L^{-1}$)	ln(Na^+) ($mg\ L^{-1}$)	K^+ ($mg\ L^{-1}$)	Mg^{2+} ($mg\ L^{-1}$)	Mg^{2+} excl. outlier ($mg\ L^{-1}$)	Ca^{2+} ($mg\ L^{-1}$)	Ca^{2+} excl outlier ($mg\ L^{-1}$)	SAR
Roof	0.148	**<0.001**	0.148	0.530	0.103	0.470	**<0.001**	**<0.001**	0.112	0.647	**<0.001**	0.180	**0.003**	**0.054**	**0.011**	0.234	**<0.001**	**<0.001**	0.154
Precip	0.353	0.509	**0.020**	0.490	**<0.001**	0.517	0.686	0.920	**<0.001**	0.182	0.173	0.960	0.281	**0.017**	0.195	0.433	**0.015**	0.889	0.190
Roof*Precip	0.613	0.477	**0.003**	0.826	**<0.001**	0.470	0.541	0.496	**<0.001**	0.217	0.126	0.055	0.956	0.510	**0.002**	0.291	**0.023**	0.408	0.943
Model P	0.333	**0.005**	**0.003**	0.842	**<0.001**	0.440	**<0.001**	**<0.001**	**<0.001**	0.084	**0.002**	0.089	**0.026**	**0.050**	**0.001**	0.147	**<0.001**	**0.001**	0.368
Model R^2	0.238	0.501	0.529	0.114	0.740	0.216	0.774	0.668	0.775	0.360	0.530	0.340	0.420	0.381	0.570	0.330	0.664	0.580	0.230

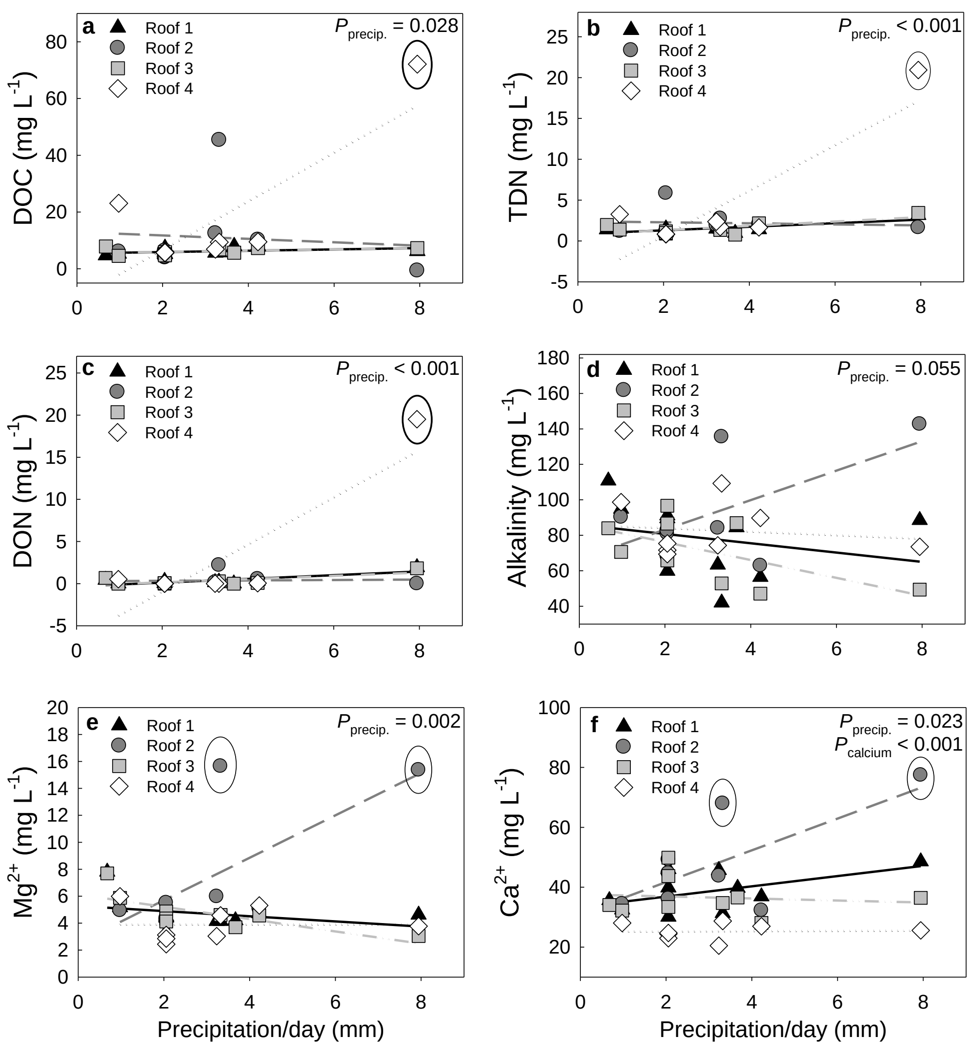

Figure 2.7 Effect of precipitation and roof on a) DOC, b) TDN, c) DON, d) Alkalinity, e) Mg^{2+} and f) Ca^{2+} in recycled green roof irrigation water. Only parameters that were significantly affected by precipitation and/or roof are shown. Circled data points were considered outliers. When they were excluded from the model significant precipitation x roof interactions disappeared.

2.3 Discussion

2.3.1 Media Chemistry

The FLL guidelines suggest that intensive green roof growing media should contain no more than 12% organic matter by mass (FLLGuidelines 2002). The GRO Green Roof Code is a best practice code for green roofs used in the United Kingdom. It suggests an organic matter content of 9% by mass (GRO 2011). The FLL Guidelines and GRO Green Roof Code recommend that the growing medium be composed of no more than 60% and 40% gravel, respectively. A proper ratio of fine and large aggregates is important in a green roof media for proper drainage while still allowing sufficient nutrient retention (Long et al. 2007). The growing medium on the roofs in this study ranged from 50-67% gravel which is slightly higher than recommended and contained less than the recommended percent organic matter for an intensive roof. Organic matter percentages ranged from 5 % in the initial media mix to 7.4 % on the youngest roof. Nutrient concentrations in media extracts showed that the green roofs' growing media held similar extractable nutrient concentrations. The only significant differences in media across the roofs were percentage of organic matter. Percent organic matter showed a decrease in OM with increasing roof age. Roof 2B is a separate raised tier of Roof 2 that was constructed at the same time and received the same media, yet at the time of our experiment it had lower organic matter than Roof 2. The only difference between them is that Roof 2B was not irrigated and relied solely on rainfall. Roof 2B had noticeably less plant cover than the other roofs which was probably due to the lack of irrigation combined with an extreme drought in 2011. The decomposing dead plant material led to an increase in DON and DOC in runoff, while a lack of plants minimized fresh organic matter input, leading to a decline in organic matter percentage when compared to the larger irrigated roof 2. The initial growing media had significantly different concentrations of EC, percent organic matter and calcium ions. The initial mix has higher EC and Ca^{2+} than the green roofs' mix likely because the young fresh growing media has not been on the roof long and has not had time for rainfall and irrigation to leach out some of the built-up salts and nutrients. The mean percent organic matter of the initial mix is at 5 % which is within the manufacturers specifications. It has not had organic matter input from actively growing plants or plant senescence thereby keeping the percentage near the original percentage.

Precipitation per day best explained the concentration trends in the media. Increasing precipitation decreased many of the measured concentrations of the media extracts including EC, SAR, DOC, NH_4^+, PO_4^{3-}, Na_+, K_+, Mg^{2+}, and Ca^{2+}. One assumption is that as the roof received more rain, salts and nutrients leached out of the media profile and into the holding tank. DON in media extracts was the only parameter that showed a significant positive relationship with increasing mean daily precipitation. Other studies have documented that precipitation events increase the concentration of DON in the soil (Michalzik et al. 2001; Tipping et al. 1999), as increased soil moisture can stimulate the breakdown of organic material into DOC and DON. Thus, even if increased precipitation leads to more DOC and DON being leached out of the soil, the production of DOC and DON was stimulated by precipitation to such an extent that media concentrations of DOC and DON still increased.

2.3.2 Runoff Quality

Runoff from the conventional roof in our study had significantly lower means of most parameters measured. Conventional roofs generally have relatively low concentrations of sodium, calcium and magnesium when compared to a green roof (U.S.EPA 2009b) because the precipitation flows over roof material that does not transfer high concentrations of these constituents. In addition, runoff from green roofs is generally a source of nitrogen (Morgan et al. 2013) and phosphorus (Kok et al. 2013) when compared to a conventional roof (Moran et al. 2004; Van Seters et al. 2009; Hathaway et al. 2008; Bliss et al. 2009). The observed differences in runoff quality between conventional roofs and green roofs are due to the leaching of ions out of the organic profile that is associated with green roofs (Monterusso et al. 2004; Hathaway et al. 2008). As expected, in our study runoff from the conventional roof had significantly lower concentrations of Na^{+}, Ca^{2+}, and Mg^{2+} than runoff from the green roofs. However, we found that only green roof 1 had higher nitrate-N and phosphorus P in the runoff when compared to the conventional roof, while N and P in runoff from roofs 2, 3, and 4 was similar to that in the conventional roof runoff. The drainage water quality from all green roofs in this experiment was comparable to green roof runoff in other studies where mean nitrate-N ranged from 0.2-70 mg L^{-1}(Morgan et al. 2013; U.S.EPA 2009b; Speak et al. 2014; Vijayaraghavan et al. 2011) and mean phosphate-P ranged from 0.06 - 2.4 mgL^{-1} (Kok et al. 2013; U.S.EPA 2009b; Teemusk and Mander 2011). Perhaps a more accurate understanding of the role that green roofs play in urban stormwater management would be a comparison of green roof runoff to other vegetated areas rather than to other non-pervious roofs. Concentrations of nitrate-N (Lang et al. 2013; Gaudreau et al. 2002), ammonium-N (Lang et al. 2013; USGS 2002; Wherley et al. 2014), phosphate-P (Lang et al. 2013; Weibel et al. 1964; Wherley et al. 2014) DON (Gallo et al. 2013; Lang et al. 2013; Wherley et al. 2014; Aitkenhead-Peterson et al. 2014), and alkalinity (Weibel et al. 1964) in this investigation are comparable to runoff from lawns and residential areas in other studies. Even when compared to a more naturalized area, the green roofs have comparable runoff concentrations of nitrate-N, phosphate-P, Na^{+}, K^{+}, Mg^{2+} and Ca^{2+}(White and Williamson 1973). In addition the concentrations in this runoff are lower or comparable to concentrations measured in streams in Texas (Aitkenhead-Peterson et al. 2011b; Steele and Jennings 1972; Aitkenhead-Peterson et al. 2009). Therefore if this runoff was to leave the site it would not further concentrate local streams.

Rain in the Houston area can have a pH as low as 4.8 (USGS 2012). Once precipitation interacts with the roof covering, the pH can change (Mason et al. 1999; U.S.EPA 2009b; Bliss et al. 2009) depending on rainfall pH and roof covering chemistry. Irrigation water pH is dependent upon the source water for the municipal tap water used. For example, a groundwater source will generally have a higher pH than surface water (USGS 1998). Water from sinks in the building is drained into the holding tanks to use for irrigation and this water is obtained from the municipal supply. Most tap water contains base cations (Park et al. 2007) which increase the buffering capacity of the water and soil (Bessho and Bell 1992) and potentially increase runoff pH. Irrigation water from the roofs was compared to municipal tap water from the building of roof 1

(Table A-2.2). In addition, runoff from parking lots and buildings can buffer the acidity caused by rain due the chemical properties of infrastructures like buildings and paved surfaces (U.S.EPA 1999b). The acidic pH of rain and the lack of alkaline irrigation likely reduced runoff pH of Roof 2B compared to the other green roofs. However the runoff pH is still above 7.5 for this roof and all 6 roofs meaning that they would not have contributed acidic water to local streams if allowed to run off the property.

Organic matter in soils is decomposed by microorganisms to soluble compounds (i.e. DOC, DON) that dissolve into the soil solution and enter the drainage system through leaching when media is saturated. Major sources for DOC are plant residues (Yang et al. 2013) and applied compost (Zhang et al. 2006). Dissolved organic carbon concentrations in roof 2B (precipitation input only) runoff were significantly higher than in the runoff from the green roofs receiving grey water irrigation (roofs 2, 3, and 4) and more similar to roof 1, the roof receiving septic discharge. In addition, roof 2B had the higher DON concentrations in runoff than any of the other roofs. The only water input into roof 2B was from natural precipitation. In 2011 a severe drought occurred, killing most vegetation on roof 2B, adding significant organic matter to the media (NOAA 2014). Succeeding precipitation events in 2012 (1227 mm precipitation) would have allowed enough moisture in the soil for this material to decompose and dissolve some of the organic matter into the soil solution.

Runoff nutrient concentrations were comparable to other green roof runoff studies conducted in Texas (Aitkenhead-Peterson et al. 2011a; Mendez et al. 2010) with the exception of roof 1 where concentrations were higher than other green roof runoff quality studies (Teemusk and Mander 2011; Vijayaraghavan et al. 2011; Berndtsson et al. 2009). Runoff from roof 1 consistently had higher concentrations of most nutrients and DOC and DON than the other roofs. Roof 1 used aerobically treated septic spray in addition to the grey water recycling system. This type of system is meant to biologically break down organic matter and sludge to an acceptable degree where it can be distributed above ground as irrigation. Although it breaks down organic matter it does not necessarily remove nutrients such as nitrate, ammonium, phosphorous, or cations such as sodium, potassium, calcium and magnesium (U.S.EPA 1992). Thus roof 1 had an additional source of organic carbon, salt and nutrient inputs into the system.

2.3.3 Irrigation

Irrigation water in the Houston, TX area comes from surface waters including rivers and lakes and ground water from the Evangeline and Chicot underground aquifers (Forrest 2013). This water is treated to potability by the municipal systems then piped to the site to be used for drinking, irrigation and other purposes. The irrigation concentrations of the green roof's recycling systems in this study were low to comparable to irrigation EC, cation, alkalinity, and SAR measurements in the Houston area and other regions in Texas investigated by Steele et al. (2012). The recycled irrigation water from all the roofs in this study is comparable to municipal tap water samples taken from the building of roof 2 (Table A-3).

A relationship between irrigation water and precipitation was expected especially since a relationship between media extracts and precipitation was observed. Constituents that leached out of the media should have been transported to the holding tank and then observed in the irrigation samples. However, this was not observed. Where a precipitation effect was observed there was also a precipitation by roof interaction. The roof by precipitation interactions were significantly influenced by one or two data points for each parameter. When the data points were removed from the model, however, the significant roof by precipitation interactions were absent. One explanation for this is the sampling method used during the experiment. At each sampling date only one sample of irrigation water was collected for each roof. This could cause one sample to have a significant effect on the model for each parameter.

Nutrient concentrations in the irrigation water were lower than those in the roof runoff. This suggests that the filtration system used on each roof was very effective at lowering nutrient concentrations. Each roof was outfitted with a first-flush diverter. The first bit of water that runs off from a roof, whether it is a green roof or conventional roof, is typically higher in salts, nutrients, and pollutants than the following runoff (Berndtsson et al. 2008; Tobiszewski et al. 2010). This is known as the first flush. First-flush diverters are efficient at capturing and excluding that water from rainwater harvesting systems. However, in our semi-closed system the first flush was released onto the parking lot where water was still captured and stored into the holding tanks. The main function of the first flush diverter was not removal of low quality water, but to reduce the chances of debris and sediments clogging up the screens before water enters the holding tank. The second method of water quality control was a sand filter. Before harvested water was dispersed as irrigation, but after storage in the holding tank, it travelled through a sand filter. Sand filters are effective at removing sediments and bacteria, and lowering biological oxygen demand but, according to the EPA, generally do little to remove nutrients (U.S.EPA 1992). However, in our system the sand filter appears to be the main avenue for nutrients to be filtered out of the system between runoff and recycled irrigation (Figure 1.2).

2.4 Summary

The conventional roof had significantly lower mean concentrations of the parameters measured in this experiment than the green roofs. It has been common practice in green roof studies to compare the runoff between green roofs and conventional roofs. However, comparing the runoff between a green roof and a local green area presents a more practical approach since the space that each green roof building occupies was originally a vegetated area. When such comparisons are made it might show that green roofs are not such high sources of nutrient runoff in urban environments.

The green roofs systems in this study behaved similarly with regards to the measured concentrations with the exception of Roof 1, which was significantly higher in many of its runoff concentrations. This was likely due to its sole difference of incorporating the aerobic septic treatment spray in addition to the recycling system for use as irrigation. It was hypothesized that the older roofs would have higher concentrations of salts and nutrients in the system and such was not the case. There was no trend with roof age of measured parameters even with Roof 1 removed from the model.

Over the one year period that the study took place, which included one of the driest years on record (2011), water quality parameters remained within acceptable boundaries for soil and plant health, regardless of roof age.

3. EFFECT OF A WATER HARVESTING AND RECYCLING SYSTEM ON PHYSIOLOGY AND FUNTION OF PLANTS ON A GREEN ROOF

Healthy plants are essential to a green roof and its intended performance. Other than offering pleasing aesthetic greenery (White and Gatersleben 2011; Ulrich 1983), plants serve multiple functions on top of green roofs. Plants take up water from the media and transpire it through their leaves which help cool the surrounding area by evaporative cooling (Givoni 1991), can reduce the effect of the urban heat island (Alexandri and Jones 2008), hold green roof media together (Zuazo 2008; Breshears et al. 2003) and also reduce the amount of runoff that leaves the roof (Carter and Rasmussen 2006). Plant canopy shades the media and improves the insulative capabilities of the roof (Barrio 1998). If the green roof is accessible to the public it can act as a green space for visitors to enjoy the landscape. Vegetation in the urban environment and on green roofs can improve ecosystem function and diversity by providing a habitat for other flora and fauna (Getter and Rowe 2006; Monterusso et al. 2005). If plant health declines then some of the beneficial properties inherent to green roofs may also decline. Appropriate media properties and adequate moisture are two parameters that can be addressed and controlled to ensure a healthy plant canopy.

The harvesting and recycling of rainwater for use as green roof irrigation poses a viable option for sustainable development. However, potential irrigation water salinity problems due to continuous recycling through the media could cause plant health to decline.

In order to assess the impact of irrigation water we designed an experiment where identical media and plant species were subjected to irrigation water of different quality on a range of green roofs where irrigation water had been continuously recycled between 1 and 6 years. We added non-irrigated and tap water irrigated controls. We hypothesize that plants located on older roofs will exhibit decreased efficiency of physiological functions such as photosynthesis, transpiration, stomatal conductance, and water potential likely due to the recycling system causing irrigation water to have higher salt concentrations.

3.1 Materials and Methods

3.1.1 Site Characteristics

The same green roofs were used in this study as with the previous study with some minor exceptions (Table 3.1). Roof 3 was excluded from the physiology experiment due to accessibility issues with equipment installation. Another roof (roof 2C) was included that was irrigated with municipal tap water only during the experiment. This roof was another raised, separate section of roof 2. The experiment lasted from April 2012 to November 2012.

Table 3.1 Roofs used in physiology study and their irrigation sources. All containers placed on the roofs were planted with *T. asiaticum*

Roof	Species	Irrigation
Roof 1	*Trachelospermum asiaticum*	recycled & aerobic septic treatment spray
Roof 2	*Trachelospermum asiaticum*	recycled
Roof 2B	*Trachelospermum asiaticum*	none
Roof 2C	*Trachelospermum asiaticum*	municipal tap
Roof 4	*Trachelospermum asiaticum*	recycled

3.1.2 Experimental Design

All green roofs were constructed the same way and with the same manufactured media. However, since all four buildings were constructed years apart, the media could have been slightly different even though it was made to the exact specifications. The same green roof media that was used for the green roofs was obtained (Nature's Way Resources, Green Roof Mix, Conroe, TX). Square planting containers (53.34 cm x 38.7 cm x 17.78 cm) were filled with media and planted with *Trachelospermum asiaticum* (Asian Jasmine) and then placed on each roof (Figure 3.1). Planted containers were inserted into the green roof media layer by digging out an area and setting them directly on top of the filter fabric of the green roof. Each container had 5 holes in the bottom for drainage. The containers received spray irrigation from their respective roof's irrigation system. Roof 2C was outfitted with a water hose sprinkler and timer at the source of municipal tap water. The timer was set to irrigate at a similar frequency to the roof's recycled irrigation. Measurements were also taken from the existing *T. asiaticum* on roof 2 as another point of comparison.

Figure 3.1 Installation of planting containers. Media was excavated down to the filter fabric layer (a). Planted containers with uniform media were placed directly on top of the filter fabric layer (b)

3.1.3 Data Collection

Data were collected four times during a five month summer measurement period. Plant gas exchange was measured using a LI-COR gas analyzer (LI-6400XT, LI-COR, Lincoln, NE). Net photosynthesis (µmol CO_2 m^{-2} s^{-1}), stomatal conductance (mol H_2O $m^{-2}s^{-1}$), internal CO_2 concentration (Ci, µmol CO_2), and transpiration rate (mmol H_2O $m^{-2}s^{-1}$) were measured. After each measurement, the sample was placed in a plastic bag and placed on ice until at the laboratory. Leaves were scanned to get projected leaf area (cm^2) in the chamber (WinRhizoPro 2007 software, Regent System, Quebec, Canada) and used to correct gas exchange measurements for the correct leaf area. Leaf samples were then dried and weighed to get dry mass (g) and calculate specific leaf area (SLA m^{-2} g^{-1}).

Plant water potential (MPa) was measured using a pressure chamber (Soil Moisture Equipment Corp., Santa Barbara). Measurements were taken between 10am-5pm on the same dates as gas analyzer samples and each from the exact same specimens. After each measurement, samples were placed in plastic bags on ice until they reached the laboratory. Samples were dried and weighed for dry mass (g).

3.1.4 Data Analysis and Statistical Design

Statistical analyses were performed using JMP statistical software (JMP 7.0, SAS, Cary, NC). Effects of the irrigation source on plant physiological measurements were analyzed through a one way ANOVA. Differences between means were determined using a student's t-test. Effects of the irrigation source and time of day on plant water potential and rates of photosynthesis, transpiration and stomata conductance were analyzed through a two-way ANOVA, where time of day was used as a continuous variable. Times of measurements were rounded to the nearest hour. *P*-values less than 0.05 were assumed to indicate significance. Results were plotted using SigmaPlot 9 (Systat Software Inc., San Jose, CA).

3.2 Results

There were no differences between planted containers in the parameters measured (Figure 3.2, Table A-4). There was also no difference between the container plants and the open roof measurements (Roof 2 est.) taken from the same species already established on roof 2. Mean net photosynthesis of *T. asiaticum* ranged from 7.6 – 10.2

μmol CO_2 m^{-2} s^{-1} averaged across all samples at all dates. Mean transpiration rate ranged from 1.9 H_2O m^{-2} s^{-1} – 3.6 mmol H_2O m^{-2} s^{-1} and was not significantly different across roofs (P = 0.214). The mean transpiration rate of the plants on Roof 1 was lower than the others but the difference was not statistically significant. Stomatal conductance followed a similar trend by roof as transpiration rate and was also not statistically significantly affected by roof (P = 0.220). Mean stomatal conductance ranged from 0.09 – 0.23 mol H_2O m^{-2} s^{-1}. Plant water potential was marginally significantly different across roofs (P = 0.095) and ranged from -0.90 MPa to -0.37 MPa, with the most negative water potentials measured for the plants on the unirrigated roof (roof 2B) and the roof irrigated with tap water (roof 2C).

Time of day influenced physiology measurements regardless of roof. Photosynthesis (P < 0.001), transpiration (P < 0.001) and stomatal conductance (P = 0.009) were significantly correlated with time of day (Figure 3.3 a-c). Photosynthesis, transpiration and conductivity measurements of *T. asiaticum* taken later in the day were lower than measurements taken earlier in the day. Water potential showed an opposite trend and was positively and significantly correlated with time of day (P = 0.011) (Figure 3.3 d). Plant water potential measurements taken later in the day were higher than measurements taken at an earlier time of day.

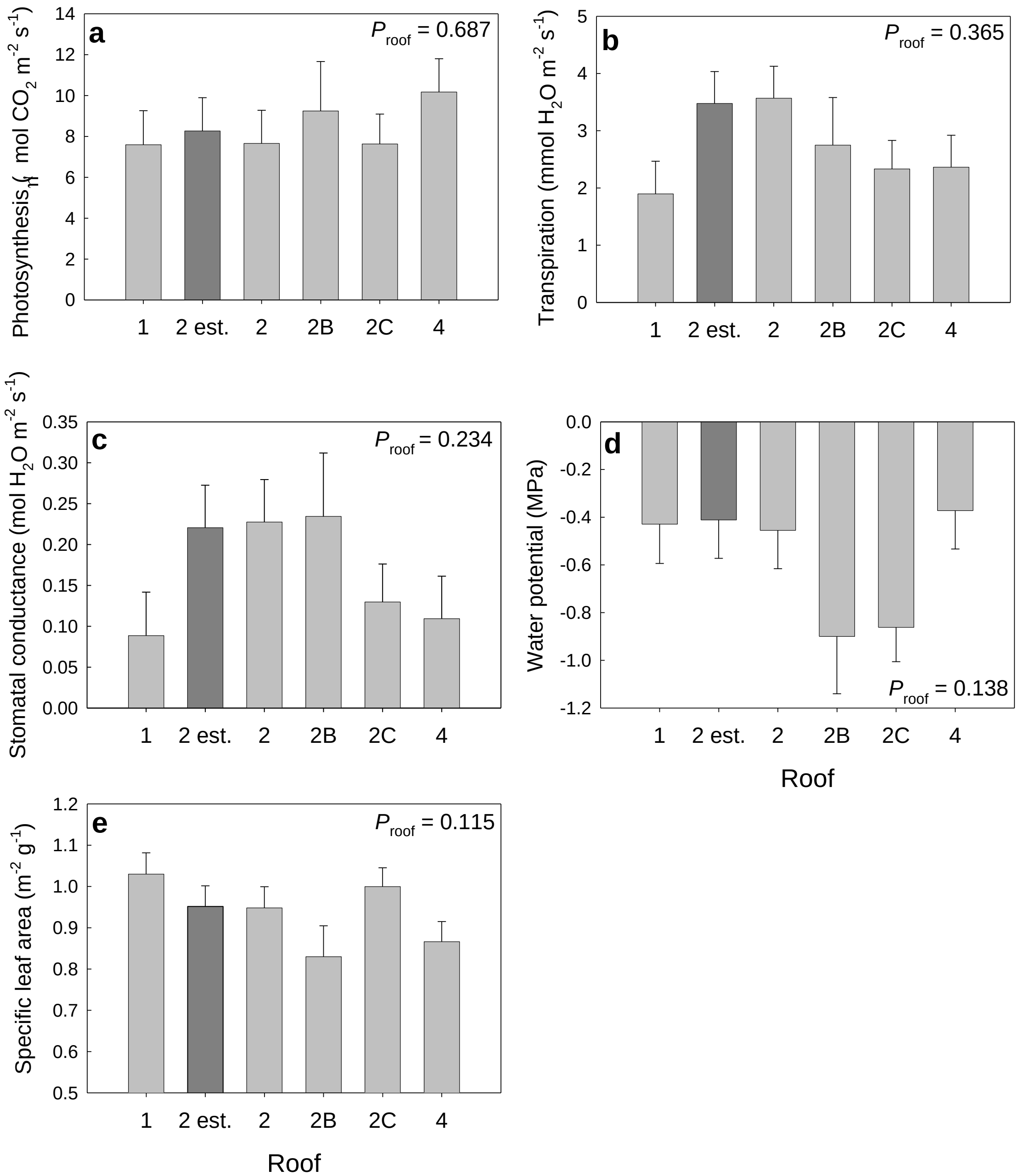

Figure 3.2 Plant physiological measurements taken from *T. asiaticum* in planted containers. Parameters included photosynthesis (a), transpiration (b), stomatal conductance (c), water potential (d) and specific leaf area (e). Roofs are in order of increasing age. *Roof 2 est.* measurements were taken from *T. asiaticum* that were already established on Roof 2 prior to the experiment (dark grey bar). *P*-values are with roof 2 est. removed from the model for uniform comparison but it is added to the graph for visual comparison. Significance was not influenced with or without these measurements included in the statistical model. Roof 2B is the unirrigated roof and Roof 2C was irrigated with municipal tap water

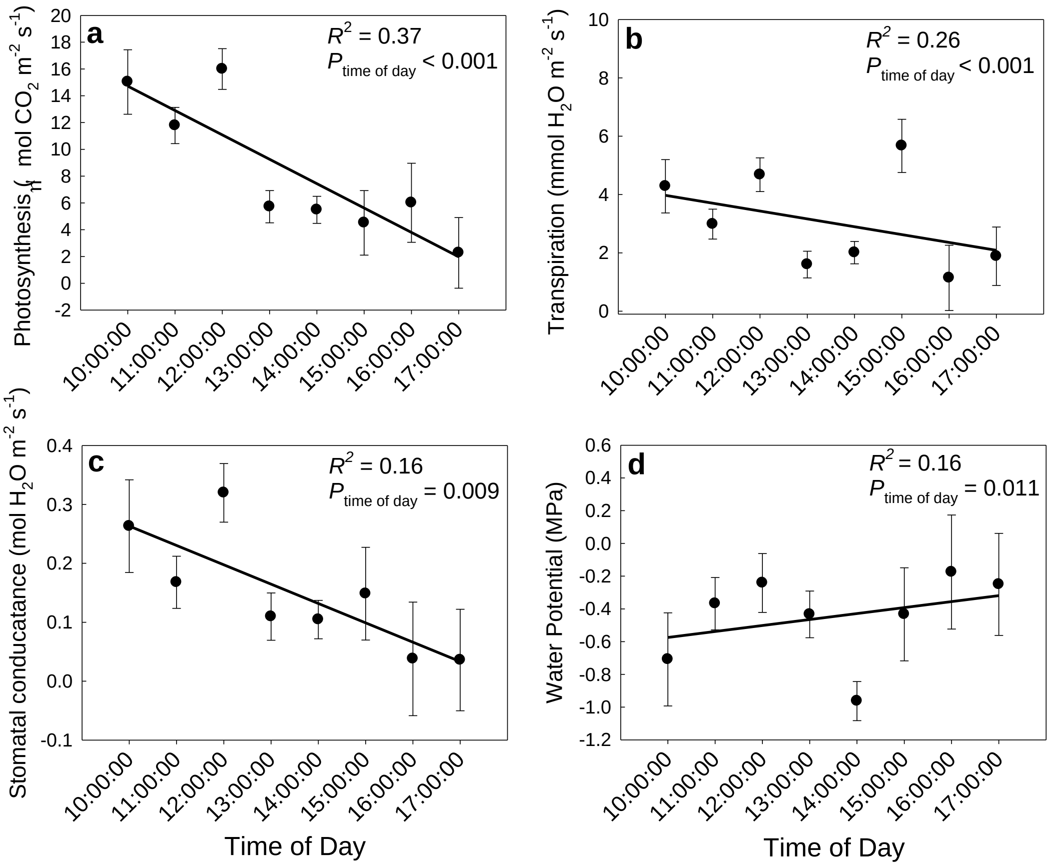

Figure 3.3 Physiology measurements plotted with time of day in which they were taken. photosynthesis (a), transpiration (b), stomatal conductance (c), and plant water potential (d)

Growing media extracts were analyzed for differences between planting containers installed on different roofs to investigate whether roof irrigation had different effects on the uniform starting media. Media extracts showed significant differences of EC, percent organic matter, TDN, Mg^{2+}, and Ca^{2+} between roofs (Figure 3.4). Containers on roof 1 (septic discharge roof) had higher mean concentrations of EC, TDN, Mg^{2+} and Ca^{2+} than most of the other roofs. Containers installed on roof 2 had significantly higher concentrations of alkalinity than the other containers. Container media on roofs 2, 2B (unirrigated) and 2C (tap water irrigated) had the lowest EC, TDN, Mg^{2+} and Ca^{2+}. Other parameters were not significant between roofs (Table A-5).

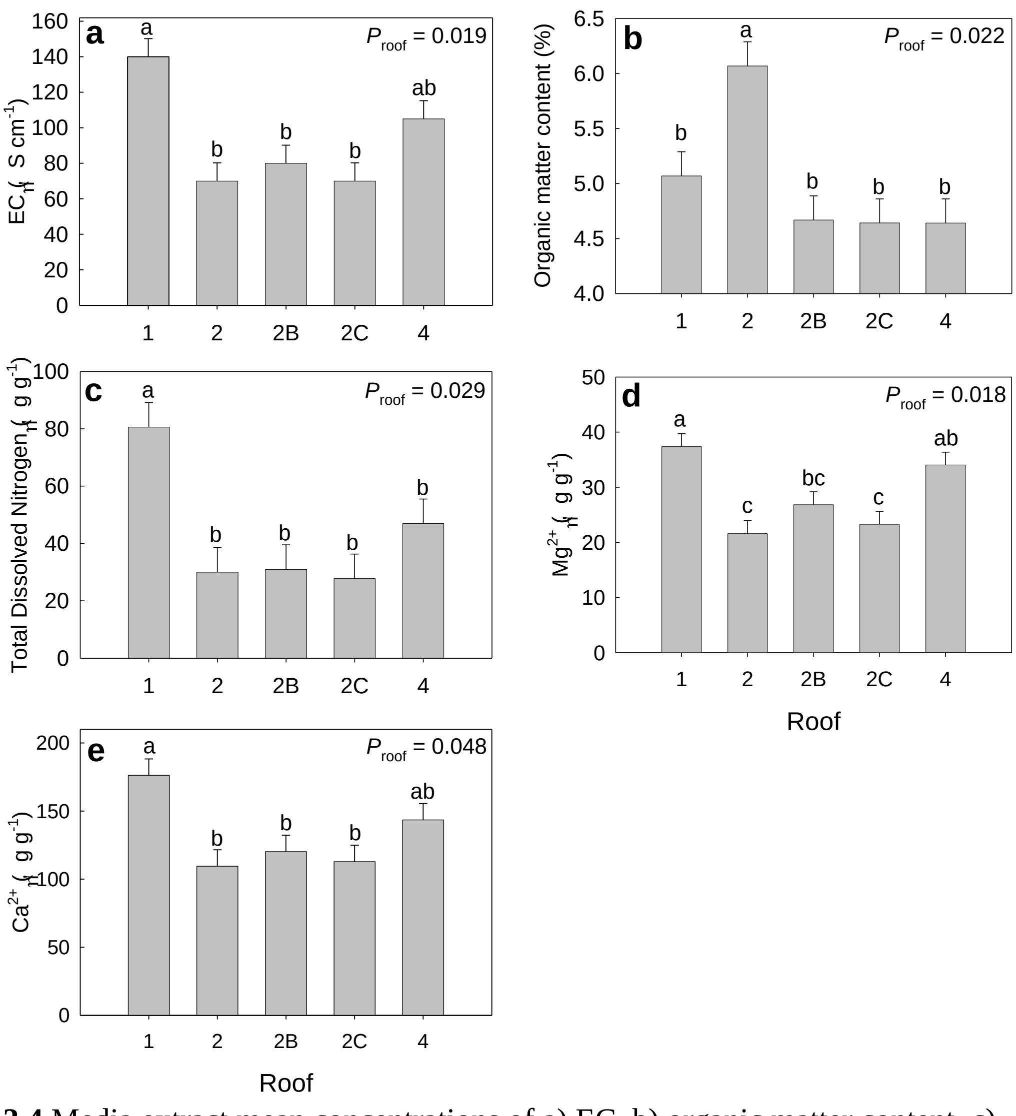

Figure 3.4 Media extract mean concentrations of a) EC, b) organic matter content, c) TDN, d) Mg^{2+}, and e) Ca^{2+} of planting containers placed on green roofs. Only significantly different parameters are shown and are indicated by different letter determined by Student's t-test at $P < 0.05$. Error bars indicate standard error

3.3 Discussion

Physiological measurements were taken from uniform planting containers planted with *T. asiaticum* and uniform starting media. Containers were installed on each roof and received the respective roof's irrigation. This addressed the issue of different media characteristics that could have influenced the study in section 2. Physiological measurements that were taken suggested that plants across all roofs behaved similarly. There were no significant differences in photosynthesis, transpiration, conductivity, or water potential between plants on different roofs. Values for water potential and rates of photosynthesis, transpiration, and conductivity were similar to other studies of ornamental species (Slootweg and Van Meeteren 1991; Sánchez-Blanco et al. 1998; Sanchez-Blanco et al. 2009; Chapman and Auge 1994). Measurements were not taken from the plants on roof 2B on the second measurement date of June 27, 2012. This was because the plants were brown and appeared dead likely due to lack of irrigation and roof 2B is the roof that relies solely on rainfall. The roof received 17.8 cm of rain between the first (May 9, 2012) and second measurement (June 27, 2012) dates but 16.51 cm were 2 days after the first measurement date with no precipitation afterwards leading up to the second measurement date. This period of drought could be responsible for the decline in plant health on roof 2B. By the third measurement date (July 25, 2012) more precipitation occurred but it was more intermittent (23.8 cm spread out between 14 days). By this date the plants had recovered, were green, and actively growing again and measurements were taken. This could have caused the lack of significance between the unirrigated roof and the others. Although it might have been significant if measurements were possible, it would likely have been due to lack of irrigation and not the actual irrigation quality itself.

The time of day in which the measurements were conducted was the most influential variable observed. It was not possible to take measurements on all roofs within a short time-frame due to length of time needed at each roof and travel time. Roofs were visited in a different order each measurement date to improve data quality. Measurements taken later in the day showed lower photosynthesis, transpirations and stomata conductivity rates. Water potential, however, showed a direct relationship with time of day. Measurements taken later in the day had a higher plant water potential than measurements taken earlier in the day. Stomata will close in response to low soil water content (Ritchie 1974) to reduce transpiration during times of high evaporative demand (Garnier and Berger 1987). The plants in this study reduced their stomata conductance as evaporative demand increased thereby reducing transpiration. The consequence of this response is reduced rate of photosynthesis due to less CO_2 uptake and increased plant water potential has been observed by others (Klepper 1968; Acevedo et al. 1979; Turner 1974).

3.4 Summary

Containers were planted with uniform growing media and plants to account for a variable starting mixes that could have influenced the study in section 2. This study aimed to determine if the recycled irrigation from each green roof system would have an influence on plant physiology and function. Physiological measurements taken from

Trachelospermum asiaticum during the experimental period did not show a significant relationship with the irrigation source. The recycled irrigation from the oldest green roof (roof 4) did not have a significantly different effect on photosynthesis, transpiration, stomatal conductance, or water potential than the younger roofs nor from the plants irrigated with municipal tap water.

The plants used in this study continued to actively grow and remain healthy during the investigation, with the exception of the plants placed on roof 2B during the month of June 2012 due to lack of irrigation. However, these plants came back after sufficient precipitation and had measurements similar to the others in this study.

This study reinforces the results from the study in section 2 concluding that the irrigation water of the green roof systems remained within acceptable boundaries for soil and plant health, regardless of roof age. The plants on all roofs remained physiologically and visually healthy.

4. MODULAR GREEN ROOF MEDIA EROSION

Installing vegetation to alleviate soil erosion is a widely used practice and has proven to be very effective as embankment plantings or for stabilizing riparian zones (Snelder and Bryan 1995). It has been suggested that the use of media only, without plants, can provide many of the same benefits as a planted green roof. However incorporating plants can optimize benefits of the roof (Lundholm et al. 2010). In addition, plant roots and their exudates bind soil particles together and hold media in place which reduces vulnerability to both wind and water erosion (Gyssels et al. 2005), while surface roots and above ground vegetation slow down sediment flow (Van Dijk et al. 1996) . Thus, the presence of plants can also play an important role in maintaining media depth on the roof (Volder and Dvorak 2013), hence indirectly contributing to both stormwater mediation and energy usage reduction benefits of the media.

My objective was to test whether the use of plants on a green roof can help prevent or reduce soil erosion and if functional group composition (succulents, herbaceous, or mixed) has an effect on erosion processes. I hypothesized that the presence of vegetation will significantly reduce erosion compared to an unvegetated green roof. Second, I hypothesized that periods of higher wind speed or greater precipitation intensity will enhance erosion, and will enhance erosion more in unvegetated areas than in vegetated areas.

4.1 Materials and Methods

4.1.1 Experimental Design

Twelve extensive green roof modules were constructed on Texas A&M University's Langford building in College Station, Texas (30° 37' 7.6"N, 96 20' 16.6"W). Six wood-framed boxes were constructed with each frame containing two TectaGreen green roof modules (Tecta America Corp®, Skokie, IL) for a total of twelve modules. Each module contained a layer of drainage cups filled with 2.54 cm of very coarse drainage media (Rooflite®drain) topped with a geotextile filter fabric (Tecta America Corp®, Skokie, IL) to keep growth media in place and prevent clogging of the drainage system. The top layer of the module consisted of 8.9 cm of growing media (Rooflite®extensive, Skyland USA LLC) (Figure 4.1a). According to manufacturer specifications, this media has a 1–5 % proportion of silting components, 0.55–0.85 g cm^{-3} dry bulk density, 0.8–0.9 g cm^{-3} saturated bulk density, 60–75 % porosity, 15–25 % maximum water holding capacity, an air filled porosity at maximum water holding capacity of 50–60 % and a saturated hydraulic conductivity of 0.5–0.8 cm s^{-1} (Rooflite 2013). The growing media meets the FLL Guidelines for extensive green roofs. Planting occurred on February 16, 2011. Three modules were left unplanted and used as a control. The other nine consisted of 3 different mixtures of plants, each replicated 3 times. Three modules contained succulents only and were planted with six *Bulbine frutescens*, six *Sedum Mexicanum*, three *Malephora lutea*, six *Lampranthus spectabilis* 'Red Shift', four *Sedum kamtschaticum*, four *Sedum tetractinum*, and six *Talinum calycinum* in each module. Three modules had a mix of succulents and herbaceous plants and consisted of six *Bulbine frutescens*, three *Graptopetalum paraguayense*, six *Stipa tenuissima,* six *Sedum Mexicanum*, three *Manfreda maculosa,* three *Lampranthus spectabilis* 'Red Shift', and six *Lupinus texensis*. The remaining three modules were planted with herbaceous plants only and consisted of three *Dichondra argentea*, three *Stemodia lanata*, six *Stipa tenuissima*, three *Myoporum parvifolium*, three *Manfreda maculosa*, and six *Lupinus texensis*. Supplemental irrigation was applied once during the experimental period, on Aug 1, 2011 at 16.9 L m^{-2} (equivalent to a 16.9 mm precipitation event) using a watering can. Each module received the same amount. The modules were set at a 2 % slope facing southeast.

4.1.2 Data Collection

Three galvanized measurement rods (170 mm length) were installed in each module on May 25th, 2011 (Figure 4.1). Each rod had a wide metal base held in place by the weight of the media above it, preventing vertical movement of the rod. Rod installation and measurements began 3 months after planting the modules to allow plants to establish. During this period modules were watered weekly, however modules were not irrigated again during the period that erosion was measured. Measurements were taken with a ruler by measuring the distance from top of the soil line to top of measuring rod. This length was subtracted from the entire length of the rod to determine media depth. An initial measurement was taken on May 25, 2011 and then once a week afterwards for two months. After this initial period, measurements were taken monthly from August 2011 through May 2012.

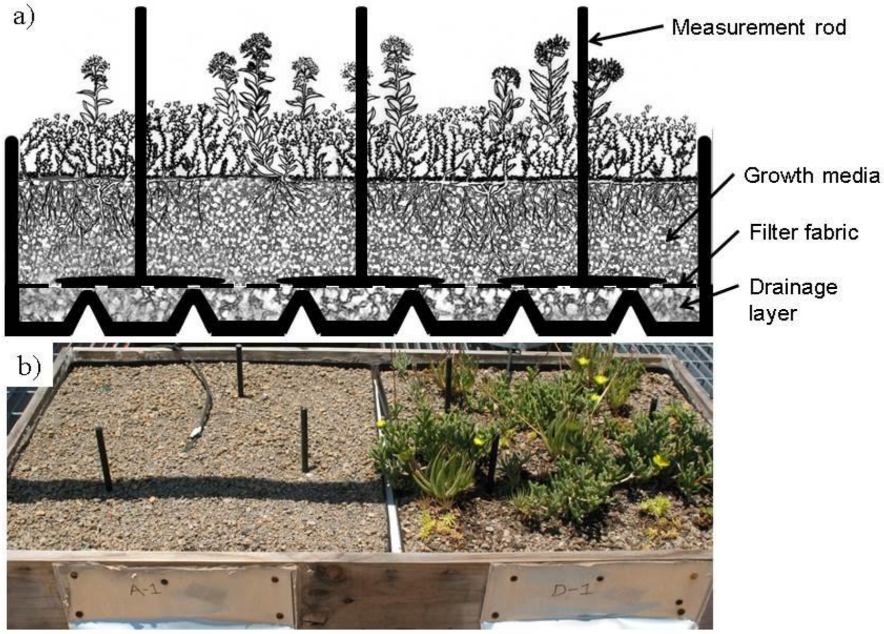

Figure 4.1 Diagram and photograph of modules. a) Cross section of the modules used in the study. Each module was 11 cm high and 61 cm wide. The rods were 170 mm in total length, depth of the growth media was 8.9 cm, and the geotextile filter fabric was installed over 162.6 cm^3 drainage cups filled with expanded shale. Schematic is not to scale. Modified from Dvorak and Volder (2013), b) Photograph of an unvegetated and vegetated module with rods installed.

Media depth on each date was calculated for each module by averaging the measurements from the three rods. Reductions in mean media depth were considered media loss, while increases in mean media depth represented media gain. Loss or gain rate (mm day^{-1}) were calculated as the amount of media loss or gain that occurred since previous measurement divided by the number of days since the previous measurement. Temperature, relative humidity, solar radiation, wind speed, wind direction, and precipitation on data was collected an hourly basis from a weather station located on the same platform as the modules.

4.1.3 Data Analysis and Statistics

All statistics and analyses were performed using JMP 10 (SAS Institute Inc., Cary, North Carolina, USA) and SigmaPlot 9 (Systat Software Inc., San Jose, California U.S.A.). Differences in mean media loss or gain over the whole measurement period were analyzed using ANOVA. To assess the impact of windspeed and precipitation rate, data were analyzed using general linear regression with media loss or gain as dependent variables, vegetation presence and types as independent factors, and mean daily maximum wind speed during a time interval and mean daily precipitation during a time interval as co-variates.

4.2 Results and Discussion

There was no significant difference in media loss or gain over the full time period between the succulent, herbaceous and mixed vegetation types ($P = 0.747$, data not shown), and thus I report only on the vegetated versus media-only comparison. Vegetated (all vegetation types) and media-only roofs did behave differently in the first three weeks after rod installation. In the first 3 weeks, vegetated modules lost considerably less (1.1 mm) media than did unvegetated modules (5.7 mm). Once the media had settled after the rod installation disturbance (after June 15, 2011) there were no statistically significant differences in media loss between vegetated (0.52 mm) and unvegetated (0.88 mm) modules over a period of nearly a year (until May 22, 2012,). Thus, the presence of vegetation was helpful in reducing erosion after initial rod installation, but appeared to have little effect once the media settled (Figure 4.2).

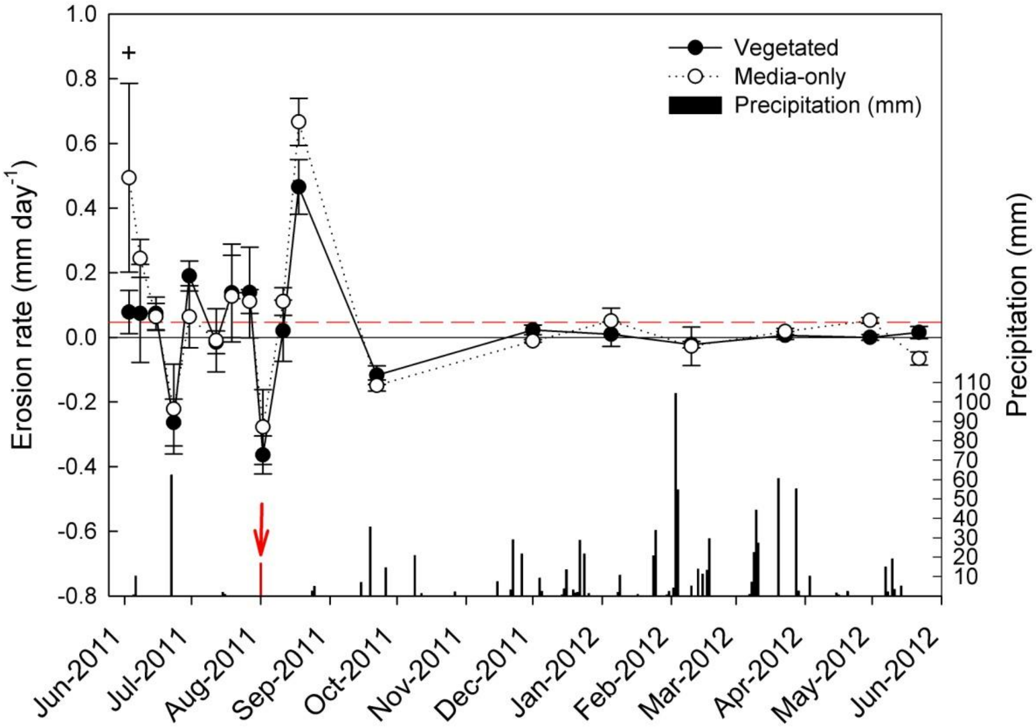

Figure 4.2 Erosion rates of media-only (open circles) and vegetated modules (solid circles) through time. Dashed red line indicates mean erosion rate and vertical bars indicate daily precipitation events. Red arrow and vertical bar indicate a manual irrigation event where 16.9 mm was applied with a watering can. + indicates a statistically significant ($P < 0.05$) difference in erosion rates between treatments.

Where I expected heavy precipitation events to increase erosion rate, it appears that large precipitation events during dry periods resulted in increased media thickness. Strong gains in media depth were observed on June 23, August 2, and September 22 when sizeable precipitation events (62.2 mm, 16.9 mm, and 35.6 mm respectively) occurred within 48 hours prior to media depth measurement. The large gains were made after precipitation events that occurred after a prolonged dry period, rather than after an even larger event that occurred when the media was already very wet (104.4 mm, February 5) and other events in March. The modules were placed on a rooftop, thus it is unlikely that any real gains in media occurred; it is more likely that media expansion occurred following saturation of the media. This explanation is supported by the lack of gain after the large event on February 5, when the media very likely was already saturated. It is possible that as media shifted, some rods may have experienced disproportionate accumulation by chance, causing an average media gain while most other rods might have experienced soil loss. A closer analysis indicated that 85% of the rods gained media depth after these three precipitation events, supporting the idea of an overall swelling of the media, rather than accumulation on a few of the rods. In addition, the average standard deviation of erosion rate before and after the precipitation events was not significantly different, suggesting that the dataset did not become more variable after each of the three large precipitation events. Thus, the gain in media depth after large precipitation events was not driven by a few rods collecting a large amount of media; rather a majority of the rods did record a gain in media depth at a consistent rate.

When average daily maximum wind speed and average daily precipitation rate over each measurement period were included in the model, I found an interactive effect of average daily precipitation and average daily maximum wind speed on erosion rate ($P = 0.014$, Table 4.1). This relationship was not affected by vegetation presence. There was no relationship between erosion rate and mean daily maximum wind speed during periods of no rain or low precipitation (< 2 mm day^{-1}). However, when precipitation rates were greater than 2 mm day^{-1} there was an inverse negative relationship between wind speed and erosion rate (Figure 4.3), suggesting that erosion rate was reduced during periods of high windspeed and high precipitation. This relationship was strongly driven by one large storm event on June 23 with both a large amount of precipitation and high windspeed (Table 4.1). During this period of high wind the modules received 62.2 mm of precipitation in an 8 hour period after a prolonged dry period. The negative erosion rate suggests that the media gained volume after this large event.

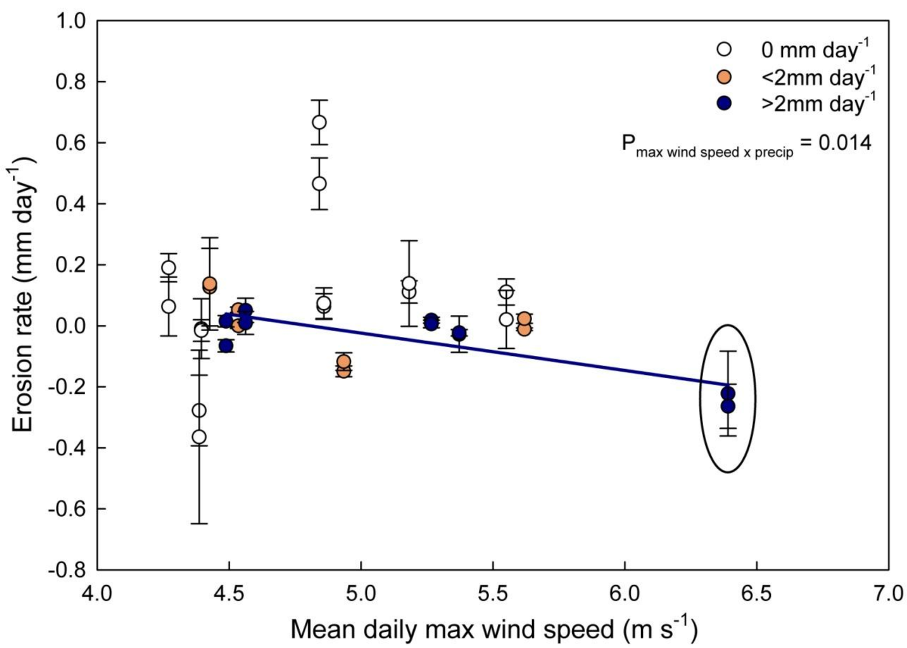

Figure 4.3 Effect of mean daily max wind speed on erosion rate. Open circles are periods with no precipitation, orange circles indicate periods with < 2mm day^{-1} precipitation, and blue circles indicate periods with > 2 mm day^{-1} precipitation. The solid blue line indicates a statistically significant negative relationship between mean daily maximum windspeed and erosion rate for periods with average daily precipitation > 2 mm day^{-1} ($r^2 = 0.228$, $P = 0.014$). There are two points for each date, one indicating the mean and standard error for vegetated modules (n = 9) and one indicating the mean and standard error for unvegetated modules (n=3). The circled plots indicate a period with high precipitation and high windspeed designated as outlier in Table 2, where 62.23 mm of precipitation fell over an 8 hour period less than 24 hours prior to the measurement

I found that vegetation did not strongly affect erosion rate after the initial media settling subsided. However, when initially installing the rods after three months of plant establishment, it was more difficult to insert rods in the planted modules due to resistance from plant roots. The presence of an established root system can help reduce the loss of soil (Gyssels et al. 2005). It is possible that all fine particles were lost during the initial disturbance event, reducing the impact of the plants. In addition, the modules were placed at a shallow slope of 2 %. It is likely that vegetation would have made a greater difference if the slope was steeper which would have increased exposure to wind and precipitation. Although I did not find noticeable changes in media depth, I did observe that the top part of the media profile became mostly composed of larger soil particles through time. It has been observed that finer particles are eroded away in a much higher percentage than larger particles (Gonzalez-Hidalgo et al. 1999). This can happen without a marked change in soil depth as most fine particles are generally located between coarser particles. In addition, it is possible that some resorting may have occurred where finer particles were moved downward in the soil profile.

Table 4.1 Statistical analysis of the presence/absence of vegetation, daily average maximum windspeed (m s^{-1}) and average precipitation rate (mm day^{-1}) for the preceding interval on green roof media erosion. *P* values <0.05 are printed in bold. See figure 3 for outlier

	Includes all events		Without outlier	
	F value	*P* > F	F value	*P* > F
Vegetation	0.10	0.747	0.05	0.831
Wind	10.6	**0.002**	0.92	0.339
Vegetation x Wind	0.43	0.511	0.04	0.843
Precipitation	0.61	0.436	1.17	0.282
Vegetation x Precipitation	0.09	0.769	0.01	0.928
Wind x Precipitation	6.30	**0.014**	0.00	0.961
Vegetation x Wind x Precipitation	0.52	0.474	0.00	0.944

4.3 Summary

The presence of plants initially helped to reduce the effects of media disturbance but did not mitigate erosion thereafter. There was no relationship between windspeed on erosion, except during events when precipitation exceeded 2 mm day^{-1}, when there was a negative relationship between windspeed and erosion. There was a temporary gain in media depth when data were collected immediately after large precipitation events, but during periods with little or no precipitation there was no effect of either precipitation or windspeed on erosion rate.

Media lost from a green roof due to erosion can create a problem, from a maintenance standpoint, if too much media is lost. In our 14-month study I found no additional benefits of vegetation presence after the initial disturbance of instrument installation. However, the presence of established vegetation can play an important role in mitigating green roof media erosion when green roofs are exposed to a period of intense disturbance, for example in areas prone to extreme wind events or when roof maintenance takes place.

5. CONCLUSION

5.1 Overview

Green roofs can play a significant role towards improving urban environment function and reducing the impact on surrounding ecosystems but also by incorporating natural aesthetics into urbanized areas. They have proven to be effective at mitigating issues associated with urban areas such as stormwater management, reducing the urban heat island effect, neutralizing acid rain, while also serving as a place for flora and fauna. For a green roof to function effectively, all components and materials should be carefully considered.

The growing media used on green roofs is crucially important to plant health. It must be lightweight so that it does not compromise building integrity but must contain ample organic matter to support plant growth, while not so much that decomposition reduces the growing media profile too much. If runoff quality control is desired, then proper starting media should be carefully selected so that it does not leach nutrients, metals, and other pollutants into the runoff.

Plants provide the aesthetics to a green roof but are also important in providing many beneficial characteristics such as stormwater management through detention and retention, insulative abilities by shading and transpiration, holding media together as well as nutrient and pollutant removal and retention. Plant selection not only depends on the climate but also the growing media characteristics and irrigation water availability.

Runoff from green roofs has been a topic of concern because of the elevated concentrations of nutrients in green roof runoff when compared to conventional roof runoff. On the other hand, the amount of runoff leaving green roofs is less due to their retention and detention capabilities. Studies have found that as much as 20-70% of the precipitation that falls on a green is retained (Bliss et al. 2009; Villarreal 2007). One mass loading studies found that green roofs reduced nitrate exports by as much as 90% when compared to a conventional roof (Van Seters et al. 2009). However, other studies found that most nutrient exports from green roofs are still greater than conventional roofs even though the total runoff from the green roofs is less (Hathaway et al. 2008; Van Seters et al. 2009). Appropriate measures should be taken to properly manage the water quality and quantity that leaves a green roof site. Such practices include limited fertilizer and compost application, proper media and plant selection, or including a rainwater harvesting system to reduce or totally eliminate runoff from the site. Rainwater harvesting systems capture fresh water that is otherwise discarded and can be used to reduce pressure put on other fresh water sources. Rainwater harvesting systems in combination with green roofs could provide dual benefits to enhance the sustainable function of urban infrastructure. This is especially true in drought prone areas like Texas and the southwest where the potential for energy savings is large and the freshwater supply can become limited.

5.2 Summary of Findings

This study aimed to determine if green roof growing media and irrigation and runoff quality would be negatively affected by a rainwater harvesting and recycling system that captures precipitation and uses to irrigate the roof. Throughout the 15 month investigative period I found that all four green roof systems were functioning normally with respect to soil and water chemistry.

Green roof growing media was not significantly different between green roofs with the exception of percent organic matter which showed a negative trend with increasing roof age. In general, runoff from the conventional roof had lower concentrations of salts and nutrients than the green roofs. This finding is not surprising and is likely due to the percolation of water through the organic profiles of the green roofs. As the water percolates through the media it acquires additional amounts of salts and nutrients and DOC and DON deposited there from decomposing organic matter, dry deposition and salts and nutrients left from evaporating irrigation water. Roof 1, which was the site of the aerobically treated septic discharge in addition to recycled water, had higher concentrations of most parameters measured compared to the other green roofs. This finding could raise some concern if runoff was allowed to leave the roof. However, at this roof and all other green roofs tested, runoff enters the roof drains and returns to the holding tank to be dispersed as irrigation again. Salt and nutrient concentrations in runoff from all the green roofs in this study were lower or comparable to other sources of urban runoff (Lang et al. 2013; Weibel et al. 1964; Gallo et al. 2013; Aitkenhead-Peterson et al. 2011b). There were some significant differences in irrigation water salt and nutrient concentrations between roofs. However, salt and nutrient concentrations of all irrigation samples were of acceptable quality for irrigation purposes and comparable to municipal tap water.

The amount of precipitation significantly influenced concentrations in the growing media extracts. Increased amounts of precipitation acted as a dilutant and lowered concentrations observed in the growing media extracts. This trend was surprisingly not observed in the irrigation sample analysis. This study took place both during a severe drought (2011) and during a year with normal rainfall (2012). During the drought, concentrations were elevated but once the sites received significant precipitation concentrations were lowered.

Plant species were similar across roofs with slight differences. Growing media samples were taken beneath similar species across roofs to determine if species had an effect on nutrient concentrations. Samples taken from under and around *Lantana spp.* and *Liriope muscari* had a higher percent organic matter than samples from *Muhlenbergia capillaris*.

To address the concern of non-uniform starting media used on each green roof, I placed containers with identical growing media on each roof that received that roof's respective irrigation. The containers were all planted with *Trachelospermum asiaticum* (Asian Jasmine) and physiological measurements were conducted to determine if irrigation influenced plant function. Measurements included plant water potential and rates of photosynthesis, transpiration and conductivity. Plants on all green roofs did not show significantly different physiological measurements. This provided further evidence that the green roof systems were functioning effectively.

Another aspect of our study was to investigate media erosion processes on extensive green roof modular trays. I found that plants helped to reduce erosion caused by disturbance but did not mitigate erosion thereafter. One surprising observation after large precipitation events was that the modules gained media depth.

5.3 Conclusion

In this study I assessed the feasibility and efficiency of combining two practices for low impact development - green roofs and rainwater harvesting systems. I was interested in determining if continued use of harvested and recycled water would have a significant impact on green roof growth media, irrigation, and in turn plant health. Our results showed that the rainwater harvesting and recycling system was an effective strategy to incorporate onto green roofs. Green roofs are sustainable practices that aim to improve our impact on the environment. However, water availability is a major concern that must be addressed during the green roof design phase. Relying on municipal tap water takes away from the low impact benefit of a green roof. Harvested rainwater is a freely obtained source of clean water that can be used for irrigation and reduce the pressures put on local water resources.

Growing media characteristics are fundamental in determining the success of a green roof and achieving the desired purpose. The media influences runoff chemistry, provides plants with support, water and nutrients, and also influences the insulative capabilities of the roof. Proper media selection combined with responsible green roof management will ensure the health of the green roof. A common practice in agriculture and ornamental landscapes is fertilization but such should be done minimally and responsibly on a green roof. While fertilizer addition might improve plant health it could contribute to the runoff quality issue; or build up in the system if the green roof has a water recycling system. Plants are the noticeable and desirable feature of a green roof. Therefore, plant health is important for maintaining aesthetics, achieving the many benefits provided by green roofs, nutrient and pollutant retention and recycling, and also reducing media loss by erosion.

To achieve maximum benefits a green roof should be designed to behave like a healthy naturally functioning ecosystem with little outside inputs. To reach such a goal a major focus should be to improve the research and literature on green roofs so that future green roof developments continue to improve in function and purpose.

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APPENDIX

Table A-1 Mean measured parameters of growing media extracts from green roofs and starting mix. Starting mix was obtained from the same manufacturer that supplies the green roofs' growing media and was engineered to the same specifications

	pH	EC	OM (%)	DOC (mg L^{-1})	TDN (mg L^{-1})	NH4-N (mg L^{-1})	NO3-N (mg L^{-1})	DON (mg L^{-1})	PO4-P (mg L^{-1})	Alkalinity (mg L^{-}1)	Na^{+} (mg L^{-1})	K^{+} (mg L^{-1})	Mg^{2+} (mg L^{-1})	Ca^{2+} (mg L^{-1})	SAR
Roof 1	7.41 (±0.12)	151.43 (±11.97)**b**	7.35 (±0.23)**a**	383.15 (±56.24)	63.13 (±5.39)	4.71 (±0.53)	33.08 (±4.23)	26.23 (±3.51)	11.1 (±2.07)	343.15 (±48.83)	147.01 (±28.57)	67.99 (±8.62)	43.75 (±5.96)	139.46 (±14.72)**b**	0.95 (±0.19)
Roof 2	7.50 (±0.14)	166.73 (±12.82)**b**	7.08 (±0.25)**a**	423.41 (±61.78)	65.81 (±5.92)	4.91 (±0.58)	26.51 (±4.70)	34.15 (±3.85)	12.55 (±2.27)	293.79 (±53.56)	169.36 (±31.39)	57.07 (±9.47)	43.01 (±6.54)	130.57 (±15.97)**b**	1.07 (±0.21)
Roof 2B	7.62 (±0.22)	167.42 (±20.55)**b**	5.8 (±0.4)**b**	337.31 (±99.01)	65.1 (±9.48)	3.63 (±0.93)	31.81 (±7.32)	28.21 (±6.17)	9.3 (±3.64)	254.57 (±85.67)	148.34 (±50.3)	68.06 (±15.18)	38.53 (±10.49)	161.56 (±24.88)**b**	0.8 (±0.34)
Roof 3	7.67 (±0.16)	129.77 (±15.06)**b**	6.18 (±0.29)**b**	444.06 (±72.55)	65.42 (±6.95)	5.52 (±0.68)	25.11 (±5.37)	35.33 (±4.52)	11.09 (±2.67)	304.94 (±62.81)	112.78 (±36.86)	56.34 (±11.12)	42.17 (±7.68)	123.43 (±18.26)**b**	0.70 (±0.25)
Roof 4	7.55 (±0.11)	132.25 (±10.44)**b**	5.44 (±0.2)**b**	459.88 (±50.32)	52.21 (±4.82)	5.57 (±0.47)	16.96 (±3.80)	30.52 (±3.14)	9.75 (±1.85)	403.1 (±44.39)	113.69 (±25.56)	57.91 (±7.72)	40.34 (±5.33)	139.46 (±13.17)**b**	0.74 (±0.17)
Starting mix	7.31 (±0.38)	315 (±50.01)**a**	5.03 (±0.72)**b**	435.36 (±207.55)	62.87 (±16.77)	2.74 (±1.89)	8.35 (±13.62)	51.78 (±12.22)	4.62 (±6.86)	293.34 (±157.35)	89.74 (±92.87)	97.49 (±33.15)	111.98 (±23.66)	344.62 (±46.55)**a**	0.34 (±0.61)
P-value	0.906	**0.018**	**<0.001**	0.778	0.493	0.321	0.072	0.247	0.805	0.469	0.772	0.564	0.118	**0.002**	0.724
R-square	0.54	0.16	0.38	0.031	0.05	0.07	0.12	0.08	0.03	0.06	0.031	0.05	0.1	0.21	0.04

Each value is the mean (±s.e.). Letters within a column denote significant differences using Student's t-test at $P \leq 0.05$. *P*-values and *R*-squared values of statistical model are located on bottom two rows of table

Table A-2 Plant species effect on green roof growing media. Organic matter content was the only parameter that showed an effect regardless of roof. When roof effect was removed and species effect was investigated within each roof, roof 4 and roof 2B showed an effect of plant species on media chemistry. Blank cells indicate a species that was absent from the roof

Species		Species effect within roof	
		Roof 4	Roof 2B
	%OM	%OM	pH
Lantana spp.	6.50 (±0.33)^{abc}	7.40 (±0.56)^{a}	-
Liriope muscari	5.61 (±0.36)^{c}	6.73 (±0.40)^{a}	-
Muhlenbergia capillaris	6.45 (±0.20)^{ab}	5.49 (±0.30)^{b}	6.37 (±0.52)^{b}
Open area	5.94 (±0.34)^{bc}	-	7.83 (±0.21)^{a}
Ruellia brittoniana	7.21 (±0.53)^{a}	-	-
Tradescantia pallida	7.47 (±0.48)^{a}	-	-
P-value	0.021	0.020	0.050
R^2	0.16	0.55	0.571

Each value is the mean (±s.e.). Superscript letters within a column denote significant differences using Student's t-test at $P \leq 0.05$. *P*-values and *R*-squared are located on bottom two rows of table

Table A-3 Mean measured parameters of recycled irrigation water from green roofs and municipal tap water collected from building of roof 1.

	pH	EC	DOC (mg L^{-1})	TDN (mg L^{-1})	NH4-N (mg L^{-1})	NO3-N (mg L^{-1})	DON (mg L^{-1})	PO4-P (mg L^{-1})	Alkalinity (mg L^{-}1)	Na^{+} (mg L^{-1})	K^{+} (mg L^{-1})	Mg^{2+} (mg L^{-1})	Ca^{2+} (mg L^{-1})	SAR
Roof 1	7.65 (±0.18)**bc**	438.9 (±34.43)**a**	6.12 (±3.78)	1.53 (±1.00)	0.94 (±0.06)**a**	0.28 (±0.29)**c**	0.34 (±0.97)	0.02 (±0.08)	78.10 (±6.58)	31.99 (±4.29)**ab**	6.94 (±0.44)	4.70 (±0.76)**b**	38.60 (±2.75)**b**	1.31 (±0.15)
Roof 2	7.97 (±0.20)**ab**	527.38 (±38.49)**a**	11.17 (±4.22)	2.20 (±1.12)	0.28 (±0.07)**c**	1.71 (±0.32)**a**	0.36 (±1.09)	0.20 (±0.09)	93.42 (±7.36)	40.88 (±4.79)**a**	6.37 (±0.49)	7.63 (±0.85)**a**	48.23 (±3.07)**a**	1.45 (±0.17)
Roof 3	7.98 (±0.19)**ab**	433.33 (±36.29)**a**	6.15 (±3.98)	1.57 (±1.06)	0.76 (±0.06)**b**	0.52 (±0.31)**bc**	0.33 (±1.03)	0.02 (±0.08)	71.11 (±6.93)	34.75 (±4.52)**a**	6.69 (±0.46)	4.76 (±0.80)**b**	36.56 (±2.89)**b**	1.45 (±0.16)
Roof 4	8.27 (±0.20)**a**	249.5 (±38.49)**b**	17.29 (±4.22)	4.05 (±1.12)	0.12 (±0.07)**c**	1.50 (±0.32)**a**	2.51 (±1.09)	0.14 (±0.09)	82.75 (±7.36)	19.11 (±4.79)**b**	8.19 (±0.49)	3.89 (±0.85)**b**	25.24 (±3.07)**c**	0.92 (±0.17)
Tap	7.22 (±0.23)**c**	418.33 (±44.45)**a**	7.10 (±4.88)	1.94 (±1.29)	0.32 (±0.08)**c**	1.35 (±0.37)**ab**	0.40 (±1.26)	0.28 (±0.10)	72.22 (±8.49)	26.91 (±5.53)**ab**	6.18 (±0.57)	4.14 (±0.98)**b**	41.14 (±3.54)**ab**	1.07 (±0.19)
P-value	**0.018**	**<0.001**	0.279	0.478	**<0.001**	**0.007**	0.540	0.225	0.221	**0.034**	0.064	**0.028**	**<0.001**	0.113
R-square	0.28	0.44	0.13	0.09	0.76	0.32	0.08	0.14	0.14	0.25	0.21	0.26	0.45	0.18

Each value is the mean (±s.e.). Letters within a column denote significant differences using Student's t-test at $P \leq 0.05$. *P*-values and *R*-squared values from statistical model are located on bottom two rows of table

Table A-4 Means of *Trachelospermum asiaticum* physiological measurements taken from uniform planting containers placed on each roof. Roof 2 est. means are from plants that were already established on roof 2. The *P*-values and R^2 values are with roof 2 est. measurements excluded from the statistical model for a more uniform comparison. Significance was not influenced with or without these measurements included in the statistical model. Roof 2B was the unirrigated roof and roof 2C was the roof irrigated with municipal tap water

	Water potential (Mpa)	Photosynthesis (μmol CO_2 m^{-2} s^{-1})	Stomatal conductance (mol H_2O $m^{-2}s^{-1}$)	Transpiration (mmol H_2O $m^{-2}s^{-1}$)	Specific leaf area (m-2 g-1)
Roof 1	-0.429 (±0.165)	7.590 (±1.668)	0.089 (±0.053)	1.896 (±0.573)	1.030 (±0.051)
Roof 2 est.	-0.411 (±0.161)	8.266 (±1.626)	0.221 (±0.052)	3.476 (±0.558)	0.951 (±0.050)
Roof 2	-0.455 (±0.161)	7.653 (±1.626)	0.227 (±0.052)	3.569 (±0.558)	0.948 (±0.051)
Roof 2B	-0.900 (±0.240)	9.241 (±2.424)	0.234 (±0.077)	2.747 (±0.832)	0.830 (±0.075)
Roof 2C	-0.862 (±0.144)	7.633 (±1.454)	0.130 (±0.047)	2.333 (±0.499)	0.999 (±0.046)
Roof 4	-0.373 (±0.161)	10.171 (±1.626)	0.109 (±0.052)	2.363 (±0.558)	0.866 (±0.049)
P	0.145	0.779	0.131	0.133	0.115
R^2	0.076	0.020	0.078	0.078	0.079

Each value is the mean (±s.e.). ANOVA using a Student's t-test at $P \leq 0.05$. *P*-values and *R*-squared values of statistical model are located on bottom two rows of table

Table A-5 Mean measured parameters of growing media extracts from containers planted with uniform starting media and *Trachelospermum asiaticum*.

	pH	EC (μs cm-^{1})	OM %	SAR	DOC (μg g^{-1})	TDN (μg g^{-1})	NH4-N (μg g^{-1})	NO3-N (μg g^{-1})	DON (μg g^{-1})	PO4-P (μg g^{-1})	Alkalinity (μg g^{-1})	Na^{+} (μg g^{-1})	K^{+} (μg g^{-1})	Mg^{2+} (μg g^{-1})	Ca^{2+} (μg g^{-1})
Roof 1	7.65 (±0.08)	140.00 (±10.25)**a**	5.07 (±0.22)**b**	0.36 (±0.06)	310.63 (±31.73)	80.61 (±8.55)**a**	2.66 (±0.15)	66.81 (±11.13)	11.14 (±2.99)	4.08 (±0.47)	146.59 (±28.59)	63.61 (±9.06)	64.31 (±13.80)	37.39 (±2.33)**a**	176.21 (±12.08)**a**
Roof 2	7.56 (±0.08)	70.00 (±10.25)**b**	6.07 (±0.22)**a**	0.49 (±0.06)	310.92 (±31.73)	30.02 (±8.55)**b**	2.66 (±0.15)	10.91 (±11.13)	16.45 (±2.99)	4.01 (±0.47)	192.12 (±28.59)	67.76 (±9.06)	47.04 (±13.80)	21.60 (±2.33)**c**	109.50 (±12.08)**b**
Roof 2B	7.76 (±0.08)	80.00 (±10.25)**b**	4.67 (±0.22)**b**	0.22 (±0.06)	311.70 (±31.73)	30.98 (±8.55)**b**	2.53 (±0.15)	14.70 (±11.13)	13.75 (±2.99)	4.21 (±0.47)	175.25 (±28.59)	33.07 (±9.06)	44.84 (±13.80)	26.85 (±2.33)**bc**	120.19 (±12.08)**b**
Roof 2C	7.59 (±0.08)	70.00 (±10.25)**b**	4.64 (±0.22)**b**	0.49 (±0.06)	312.90 (±31.73)	27.74 (±8.55)**b**	2.68 (±0.15)	10.81 (±11.13)	14.26 (±2.99)	4.22 (±0.47)	204.05 (±28.59)	69.47 (±9.06)	36.86 (±13.80)	23.31 (±2.33)**c**	112.82 (±12.08)**b**
Roof 4	7.66 (±0.08)	105.00 (±10.25)**ab**	4.64 (±0.22)**b**	0.24 (±0.06)	286.09 (±31.73)	46.95 (±8.55)**b**	2.53 (±0.15)	34.32 (±11.13)	10.10 (±2.99)	3.26 (±0.47)	197.43 (±28.59)	39.24 (±9.06)	40.65 (±13.80)	34.04 (±2.33)**ab**	143.42 (±12.08)**ab**
P	0.502	**0.019**	**0.022**	0.071	0.965	**0.029**	0.908	0.061	0.611	0.613	0.652	0.097	0.687	**0.018**	**0.048**
R^2	0.43	0.87	0.86	0.78	0.09	0.84	0.16	0.79	0.37	0.37	0.34	0.74	0.32	0.87	0.81

Each value is the mean (±s.e.). Letters within a column denote significant differences using Student's t-test at $P \leq 0.05$. *P*-values and *R*-squared values of statistical model are located on bottom two rows of table